CITA SET II Project

Sustainable Emission Test for diesel vehicles involving NO_x measurements

Annexes to the Final Report

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Table 1 - Document history.

Version	Date	Author	Reason for change
v.01.00	6/01/2019	All	

Contents

Annexes

1. Type approval emission Limits

Diesel	Date	CO	NMHC	NO_x	HC + NO_x	PM
Euro 1	July 1992	2.72	-	-	0.97	0.14
Euro 2	January 1996	1.0	-	-	0.7	0.08
Euro 3	January 2000	0.64	-	0.50	0.56	0.05
Euro 4	January 2005	0.50	-	0.25	0.30	0.025
Euro 5a	September 2009	0.50	-	0.180	0.230	0.005
Euro 5b	September 2011	0.50	-	0.180	0.230	0.005
Euro 6	September 2014	0.50	-	0.080	0.170	0.005
Petrol	**Date**	**CO**	**NMHC**	**NO_x**	**HC + NO_x**	**PM**
Euro 1	July 1992	2.72	-	-	0.97	-
Euro 2	January 1996	2.2	-	-	0.5	-
Euro 3	January 2000	2.3	-	0.15	-	-
Euro 4	January 2005	1.0	-	0.08	-	-
Euro 5	September 2009	1.0	0.068	0.060	-	0.005
Euro 6	September 2014	1.0	0.068	0.060	-	0.005

Table 2 - Type approval emission Limits (g/km) of the successively introduced Euro emission standards for passenger cars

2. Technologies for the control of NO_x emissions

Diesel engines run almost always in a lean environment, it is with an excess of air. Temperature is rising when the air is compressed in the cylinders. At the moment when the fuel is injected it will auto ignite due to the suitable temperature and conditions that are created in the cylinders.
Stoichiometric engines emit more engine-out NO_x than lean engines, but these are relative easy to control with after treatment systems. PM and NO_x emissions are for diesel engines a concern and a challenge to control, more than the HC and CO emissions due to the lean operation.
PM emissions were the subject of earlier CITA studies (CITA, 2011; CITA, 2015). This study will focus on the NO_x emissions of diesel vehicles. Technologies for reducing NO_x include in-cylinder as well as after treatment technologies. The most important in-cylinder emission control systems are (Posada, Bandivadekar & German, 2012):

- Fuel injection
- Air handling
- EGR

Tighter NO_x emission levels (For Europe from 0,5 g/km for Euro 3 vehicles towards 0,08 g/km for Euro 6; for type approval emission limits see Annex 1) require after treatment control. Bischop and Stedman (2008) concluded in their study of US national wide datasets of 10 years (1997-2007) remote sensing that the majority of on-road emissions reductions over the years are the results of continued improvements in function and durability of vehicle emission control systems.

In this chapter the in-cylinder EGR emission control and the main after treatment systems for reducing NO_x will be discussed after an introduction on the formation of NO_x in diesel engines.

2.1. Formation of NO and NO_2 in diesel engines

The major part of the NO emissions is formed from the diesel combustion of near-stoichiometric fuel-air mixtures by the oxidation of atmospheric nitrogen via the extended Zeldovich mechanism[1] (Heywood, 1988):

$$O + N_2 \leftrightarrow NO + N$$

Equation 1: Formation of NO, Zeldovich part 1

$$N + O_2 \leftrightarrow NO + O$$

Equation 2: Formation of NO, Zeldovich part 2

$$N + OH \leftrightarrow NO + H$$

Equation 3: Formation of NO, Lavoie, Heywood & Keck (1970)

The formation of NO is highly temperature dependent. The forward reaction of Equation 1 and the reverse reactions of Equation 2 and Equation 3 have large activations energies with temperature ranges

[1] Zeldovich was the first to suggest the importance of reactions equation 1 and 2. Lavoie, Heywood & Keck (1970) added equation 3 to the mechanism (Heywood, 1988).

of 2000 K – 5000 K, 1000 K – 3000 K and 2200 K – 4500 K respectively. NO stays around during cooling since the reverse reaction is very slow.
The contribution of fuel nitrogen as a source of formation of NO is less significant than the Zeldovich mechanism.
At typical flame temperatures the NO_2/NO ratio should be very small taken into account chemical equilibrium considerations. It is true for spark ignition engines, but for Diesel engines NO_2 can be from 10 % up to 30 % of the total NO_x emissions. NO_2 is formed since the produced NO, formed in the flame zone can be rapidly converted to NO_2 by the reaction explained in Equation 4.

$$NO + HO_2 \rightarrow NO_2 + OH$$

Equation 4: Formation of NO_2

However, NO_2 can be converted back to NO via Equation 5.

$$NO_2 + O \rightarrow NO + O_2$$

Equation 5: NO_2 is converted back to NO

Equation 5 will be less effective when the NO_2 formed in the flame is quenched by mixing with cooler fluids. This is also what happens with the use of exhaust gas recirculation (EGR). Diesel Engines at light loads have a widespread of cooler regions which could quench the conversation back to NO, and thus a higher fraction of NO_2 occurs at light loads and depends on engine speed. (Heywood, 1988).
It is clear that the diffusion flame is the place where oxygen is available together with nitrogen at high temperature and thus of the diesel combustion process, the ideal region for the formation of NO_x.

Controlling nitrogen oxides (NO_x) emissions from Euro 6 diesel passenger cars is one of the biggest technical challenges facing car manufacturers. Some main technologies are available for this purpose:

- inner-engine modifications coupled with exhaust gas recirculation (EGR);
- lean-burn NO_x absorbers (also called lean NO_x traps, or LNTs);
- Selective Catalytic Reduction (SCR).
- Lean NO_x catalysts (also called hydrocarbon-SCR)

2.2. Exhaust Gas Recirculation (EGR)

Exhaust gas recirculation (EGR) is used in both gasoline and diesel engines. A fraction of exhaust gas is rerouted to the combustion chamber where it dilutes the incoming air by replacing oxygen with carbon dioxide and water vapour to lower the local flame temperature and the production of engine-out NO_x. Although the principle in both engines is the same, the way EGR initially was applied to those two engines is different. Since gasoline engines works with a stoichiometric air-fuel mixture and the torque and power output of the engine are required to main constant with and without an EGR, the EGR mass trapped in the engine is in addition to the mass of air-fuel mixture. A diesel engine, on the other hand, uses as much air as is practicable to trap at a given engine running condition. Application of EGR results of the displacement of the intake air by the added EGR volume and thus less trapped air in the cylinder will be available for combustion. The amount of fuel injected for a given power output and torque is constant so that with EGR the engine will operate with a lower overall air-fuel ratio. Ladommatos, Abdelhalim & Zhao (2000) concluded in their research that adding EGR to the air flow rate of a diesel engine (like with gasoline engines), rather than displaying some of the inlet air, appears to be a more beneficial way since the increased particulate emissions would be less.

There are two types of EGR:

- high-pressure EGR captures the exhaust gas prior to the turbocharger;
- low-pressure EGR exhaust gas is drawn after the diesel particulate filter (DPF) and returns it to the intercooler. This system ensures that large amounts of particulate matter are not recirculated to the engine which would result in accelerated wear in the engine and soot build up in EGR pipes.

Both approaches can be used in combination (Yang et al, 2015).

This way of reducing NO_x occurs with lower thermal efficiency and higher PM emissions following the NO_x-PM trade-off. This trade-off restricts the use of EGR to intermediate and low engine loads.

Ladommatos et al. (2000) investigated the effects of exhaust gas recirculation on diesel combustion and emissions. They separated five effects:

- Reduction of the inlet charge mass (thermal throttling effect of EGR)
- Reduction in the oxygen concentration of the inlet charge (dilution effect)
- Introduction of combustion products into the inlet charge (chemical effect)
- Rise in the heat absorption capacity of the inlet charge (thermal effect)
- Rise in the temperature of the inlet charge.

These five effects could be explained by using Figure 1.

- Reduction of the inlet charge mass is seen in Figure 1 where the mass flow rate is reduced from 49 g/s to 42 g/s after the application of the hot EGR. The replacement of relatively dense cool air by less dense hot EGR gives a rise in the inlet charge temperature which leads to a drop in engine volumetric efficiency and thus a reduction in charge mass rate. The reduction in inlet charge mass is also known as the thermal throttling effect of EGR and raises the PM emissions. EGR cooling would ameliorate the engine volumetric efficiency, and thus reduce the inlet charge mass rate

- EGR causes a substantial reduction in the oxygen mass flowrate. The main part is related by the lower volumetric efficiency (thermal throttling), but a part is caused by the fact that the EGR is less rich in oxygen than the air it is replacing. Dis part of reduction of the oxygen concentration is known as the dilution effect of EGR. This effect where O_2 in the inlet charge is replaced by CO_2 and water vapour is the most important for the changes in NO_x and particulate emissions. The reduction of O_2 concentration in the intake air reduces the flame temperature significantly.

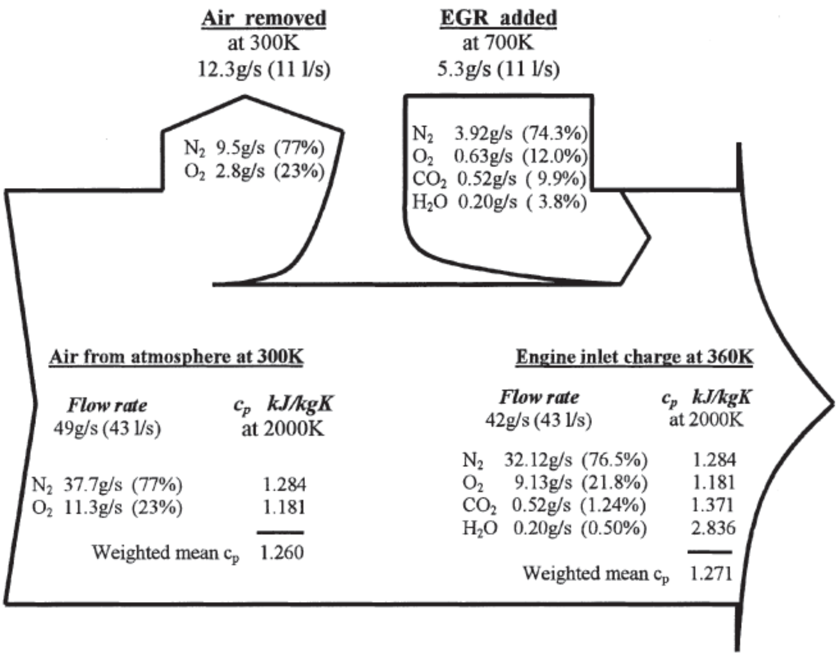


Figure 1 - Analysis of inlet charge composition. (Taken from Ladommatos et al, 2000).
25% of the engine inlet air is replaced by hot EGR and diesel engine at 32:1 air-fuel ratio.

- EGR contains carbon dioxide (CO_2) and water vapour (H_2O). These combustion products can dissociate at high temperature to chemical radicals e.g. atomic oxygen and hydroxyl which could participate in the formation of NO (Zeldovich mechanisme). This chemical effect has only a minor influence on NO_x and particulate emissions.

- Due to both carbon dioxide and water vapour, the reacted exhaust gas components, having higher specific heat capacity values c_p than the replaced components nitrogen and oxygen, the use of EGR will have the so called thermal effect as the average specific heat capacity c_p of the inlet charge will be a little higher (+/- 1%). By this effect the combustion temperature is lowered. However, since the change in heat capacity is minor in diesel engines, the thermal effect for NO_x reducing in considered insignificant.

- Finally, when intake air is mixed with hot EGR the intake charge will have a higher temperature and consequently leads to a higher flame temperature. The increase of temperature result in both higher NO_x emissions and in substantially higher emissions of PM. Therefor the recycled exhaust gas needs to be cooled as also suggested by the thermal throttling effect of EGR.

The effect of EGR on emissions can be seen in Table 3 which contains the regulatory emissions from 3 vehicles tested over the Type 1 type approval test during the Low Emission Diesel Research study when the vehicles' EGR units were operational and disabled (Norris, 2005). The size of increase in NO_x for these 3 vehicles caused by failure of an EGR unit as an average percentage relative to when the EGR unit was operational was +87%.

Vehicle	Euro spec	EGR unit	CO_2 (g/km)	CO (g/km)	THC (g/km)	NO_X (g/km)	Particulates (g/km)
Vehicle 1 Passenger car 1.8 litre DI with turbo, oxycat and EGR 10,750 mileage	II	Operational	165.2	0.269	0.021	0.454	0.083
		Disabled		0.204	0.022	1.010	0.030
Vehicle 2 Passenger car 2.0 litre DI common rail with turbo, oxycat and EGR 18,700 mileage	III	Operational	133.0	0.038	0.001	0.394	0.042
		Disabled	136.8	0.038	0.006	0.939	0.020
Vehicle 9 Passenger car 1.9 litre turbocharged, oxycat and EGR ? mileage	II	Operational	161.4	0.444	0.045	0.696	0.028
		Disabled	163.9	0.076	0.268	0.934	0.083

Table 3 - The effect of EGR operation on emissions performance Type 1 test. (Created from Norris, 2005)

2.3. Lean NO_x trap (LNT)

In a Lean NO_x trap (LNT) NO_x is absorbed onto a catalyst during lean (i.e. oxygen rich) engine operation. When the catalyst is saturated, the system is regenerated in short time of fuel-rich operation during which NO_x is catalytically reduced (Yang, Franco, Campestrini, German & Mock, 2015).

In the white paper of the Manufacturers of Emission Controls Association [MECA] (2007), the mechanism is explained:

1. Conversion of NO to NO_2 using an oxidation catalyst e.g. a noble metal substrate like platinum
2. Storing NO_2 as nitrate on alkaline earth oxides. Both oxidation steps (point 1 & 2) occur in the same device and works in a temperature windows (250°C to 500°C)
3. Regenerations occurs in two steps:
   a. In a one or two seconds rich operation the stored NO_x is desorbed
   b. Provide the condition for a conventional three-way catalyst mounted downstream to reduce NO_x to nitrogen.

Lean NOx traps absorb also sulphur oxides. Therefore, fuels with very low sulphur content like European "zero" sulphur fuel which contains less than 10 ppm sulphur are required. Periodically the system has to run an automatically short "de-sulphating" cycle under rich conditions and high temperatures to remove them. (http://www.aecc.be/en/Technology/Adsorbers.html).

For smaller lean burn passenger cars the LNT is the leading $DeNO_x$ concept. These vehicles have a limited space which makes urea usage (SCR) difficult. LNT efficiency is normally up to 80 % which is lower than the SCR systems which have efficiency rates above 95 % (Johnson, 2013).

The mean challenges for this technology are according to Schnitzler (2009):

- $DeNO_x$ regeneration by engine internal measures in terms of drivability and driver transparency
- Limited $DENO_x$ regeneration operation area
- Sulphur poisoning / desulphurization
- Reliable desulphurization strategy
- Long-term stability / thermal aging
- $DeNO_x$ and $DeSO_x$ management / complexity of after treatment control

2.4. Selective Catalytic Reduction (SCR)

A SCR system reduces NO_x to gaseous nitrogen and water in the presence of ammonia. The transportation of pure ammonia is not desired and advisable. Most light-duty applications use an aqueous urea solution (diesel exhaust fluid AdBlue™) as an ammonia precursor (Yang et al., 2015).

A typical SCR system consists of three different catalysts in series after the urea injection point (Hussain, Palaniradja, Algumurthi & Manimaran, 2012):

- Hydrolysis catalyst which converts the urea to ammonia (NH3) and carbon dioxide;

- SCR catalyst where the ammonia reacts with NO_x to form nitrogen and water.
  The conversion efficiency is a function of exhaust gas composition (NO_2 to NO ratio). The three common NO_x reduction reactions are (MECA, 2007):

  $$4NH_3 + 4\,NO + O_2 \rightarrow 4N_2 + 6H_2O$$

  Equation 6: SCR NO_x reduction reaction 1

  $$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$$

  Equation 7: SCR NO_x reduction reaction 2

  $$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O$$

  Equation 8: SCR NO_x reduction reaction 3

  Vanadia based catalyst (first generation) shows better low temperature conversions than iron zeolite catalysts. However, the latter has no efficiency drop off above 400°C, but maintains peak efficiency above 500°C.

- Oxidation catalyst to avoid ammonia slip during transient operation

Applying SCR to diesel-powered vehicles provides simultaneous reductions of NO_x, PM (up to 20% - 30%) and HC (up to 80%) emissions (MECA, 2007). It allows diesel engine developers to take advantage of the trade-off between NO_x, PM and fuel consumption.

The quantity of injected urea needs to be carefully controlled:

- too little may cause some NO_x to pass through the after-treatment system unconverted,
- too much will cause ammonia to be emitted from the tailpipe.

The aim is to model the engine-out NO_x sufficiently accurate so that engine-out NO_x emissions may reduce the after-treatment requirement e.g. engine-out NO_x sensors and ammonia oxidation catalysts may be deleted (Cambustion, n.d. a). In an open loop system, urea is added at a rate calculated by estimating the amount of NO_x present in the exhaust stream based on parameters as rpm, exhaust temperature, backpressure and load. The close loop system uses NO_x sensors that directly measure the NO_x concentrations in the exhaust.

SCR technology is still improving. The $DeNO_X$ efficiency has been increased over the years from 94% in 2012, over 94% in 2013 and should be 96% today in 2016. Latest research has focussed on high temperature durability and the performances at low temperature (175°C – 200°C). They increased by 15% from generation 3 to the generation 5 SCR's. Best performances are to be noticed around 275°C. (Johnson, 2013; Johnson, 2014).

The mean challenges for this technology are according to Schnitzler (2009):

- Reliable urea injection
- Uniform ammonia distribution in the exhaust
- NO_X neutral SCR-catalyst heating-up strategy
- Dosing strategy
- Ammonia slip
- Vehicle package
- System costs

2.5. Lean NO_x catalysts (hydrocarbon-SCR)

In a lean NO_x catalyst, hydrocarbons, as opposed to ammonia in an SCR catalyst, are used to create a rich microclimate in order to reduce NO_x in a lean exhaust. The hydrocarbons in the exhaust can either be the HC's present in the exhaust after the combustion (by e.g. in-cylinder injection modifications) or additional fuel that is direct injected into the exhaust gas. (Hussain et al, 2015; http://www.aecc.be/en/Technology/Catalysts.html).

The catalyst works efficiently only in a tight temperature window. Lean NO_x catalysts achieve in general up to 35 % efficiency (although higher efficiencies of 70 % are shown), but the need of a hydrocarbon reductant gives a fuel penalty of up to 6% (Hussain et al, 2015). The advantage of this system is that you no longer need to use an additional reductant such as urea.

Lean NO_x catalysts are used in the U.S. for diesel retrofit applications (MECA, 2007).

2.6. Combined LNT / SCR NO_x reduction technologies

The market shares of the different NO_x control technologies are presented for the EU and the US in Figure 2 and Figure 3. As already mentioned the market share for Diesel vehicles in Europe is significantly higher than in the US. In Europe the LNT technology is mostly used, in contradiction with the SCR technology in the US. Combined LNT/SCR technologies were introduced earlier in the US than in Europe.

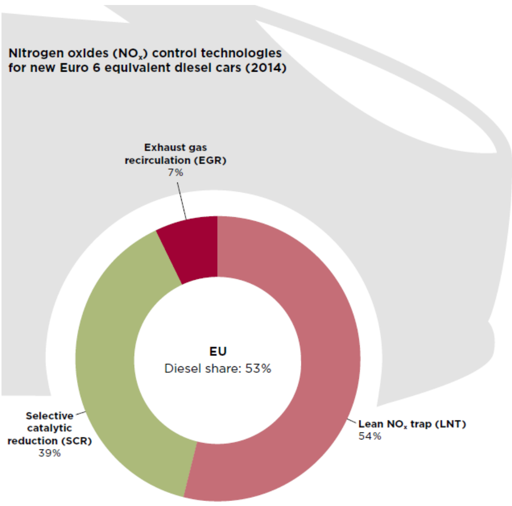


Figure 2 - NO_x control technologies in EU. (Taken from ICCT, 2015)

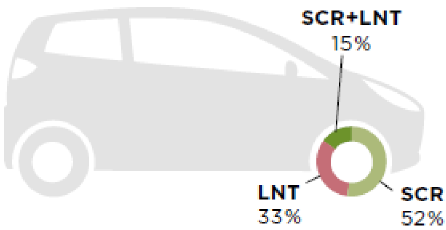


Figure 3 - NO_x control technologies in US. Diesel market share in US: 0.8 %. (Taken from ICCT, 2015)

The available after treatment solutions present a great variety. Different types of catalysts, mainly V_2O_5, WO_5, TiO_2 or zeolite formulations (Fe-ZSM5 and Cu-ZSM5) are used in the automotive industry (Chatterjee, Koci, Schmeisser, Marek Weibel & Krutzsch, 2010). Furthermore, different concepts are used e.g. in wall-flow, flow-through, single-layer, dual-layer, DPF with LNT coating or DPF with SCR coating technologies.

Based on the engine load map as seen in Figure 4 AECC, the Association for Emissions Control by Catalyst indicate that for different areas of the engine load map other abatement technologies applies optimally and have the best $DeNO_x$ efficiencies. $DeNO_x$ optimization is possible by combining different technologies to reach optimum emission reduction.

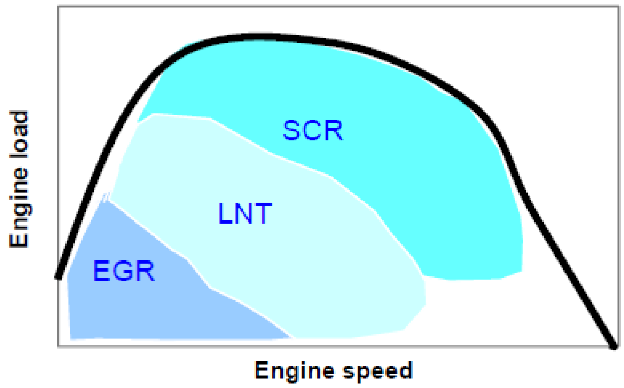


Figure 4 - figure descriptive technologies effectiveness from $DeNO_x$ optimalisation (Taken from the Association for Emissions Control by Catalyst [AECC], 2015.)

An after treatment system layout has to be designed for each individual vehicle application, taking into account decisive factors as required NO_X conversion rates, specific boundaries of the legislative test cycles and available space in the vehicle (Schnitzler, 2009).

Moreover, combined LNT/SCR technologies have the advantage not requiring separate on-board reductants like urea. This principle is explained in Figure 5.
In the LNT, during the regeneration time (rich environment for a few seconds) ammonia is formed which is then stored in the SCR catalyst. During lean operation primarily NO_x will be reduced by the LNT and the SCR uses the stored ammonia to further reduce NO_x.

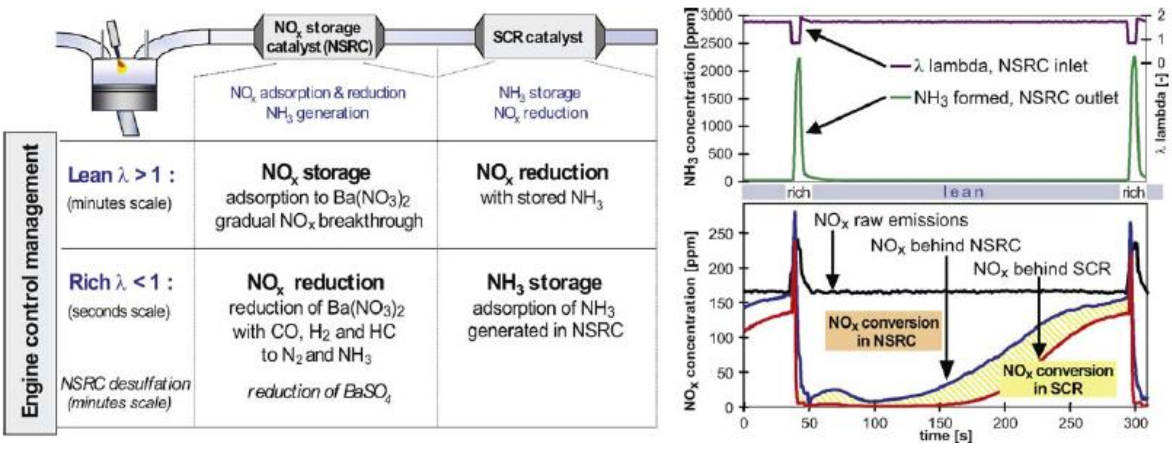


Figure 5 - Principle of the combined gas after treatment system. (Taken from Chatterjee et al., 2010)
Note: NSCR = NO_x reduction catalyst or lean NO_x trap LNT.

These LNT or SCR combinations can also be combined with DPF of DOC so that different possibilities are described, e.g.:

- LNT – DPF (Schnitzler, 2009)
- DOC / DPF – LNT (Schnitzler, 2009)
- LNT(A) / DPF – LNT(B) (Schnitzler, 2009)
- DOC – Mixer – SCR – DOC – DPF (Schnitzler, 2009)
- DOC / DPF – Mixer – SCR / DOC (Schnitzler, 2009)
- LNT – SCR in a parallel design via bypass over the LNT (MECA, 2007)
- LNT – DPF – SCR (MECA, 2007)

Possible abatement systems are also shown in Figure 6.

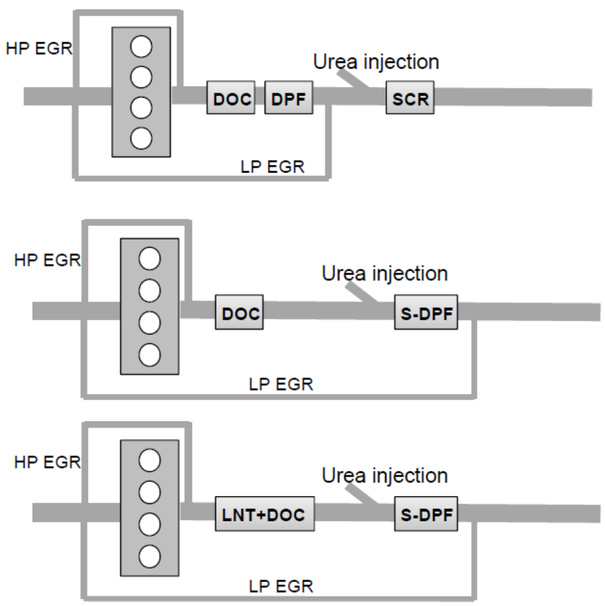


Figure 6 - (Taken from the Association for Emissions Control by Catalyst [AECC], 2015.)

2.7. Overview of the main technologies

	Lean NO_x trap (LNT)	Selective catalytic reduction (SCR)	Exhaust gas recirculation (EGR)	Combined SCR and LNT (SCR+LNT)
Principle	NO_x is adsorbed onto a catalyst during lean engine operation. When the catalyst is saturated, the system is regenerated in short periods of fuel-rich operation during which NO_x is catalytically reduced	A catalyst reduces NO_x to gaseous nitrogen and water in the presence of ammonia. Most light-duty applications use an aqueous urea solution (diesel exhaust fluid, AdBlue™) as an ammonia precursor	A fraction of exhaust gas is rerouted to the combustion chamber to lower combustion temperature and the production of engine-out NO_x. For *high-pressure EGR*, exhaust gas is drawn from upstream of the turbine; for *low-pressure EGR*, exhaust gas is drawn from after the DPF. Both approaches can be used in combination	An SCR unit downstream of the LNT allows higher NO_x conversion efficiencies. The ammonia synthesized by LNT reacts with NO_x in the SCR
Typical application	Light-duty vehicles with engine displacements below 2 liters (<2.0 L)	Light-duty vehicles with engine displacements above 2 liters (>2.0 L)	Widespread deployment from Euro 3 to Euro 6 The application of EGR and other NO_x control technologies is not mutually exclusive; SCR tends to be used in combination with EGR	Light-duty vehicles (high-end, larger vehicles)
Estimated cost per vehicle*	$320 (engines <2.0 L) $509 (engines >2.0 L)	$418 (engines <2.0 L) $494 (engines >2.0 L)	$142 (engines <2.0 L) $160 (engines >2.0 L)	
Advantages	70-90% efficiency at low loads Good durability and NO_x reduction performance More economical for engines less than 2.0 L No additional reductant tank is needed (lower packaging constraints) Reductant fluid not required (no refills needed)	Up to 95% NO_x conversion efficiency More economical for engines > 2.0 L, may provide better fuel economy/lower CO_2 emissions	No additional onboard hardware is needed Reductant fluid not required	Good NO_x control performance at low temperatures Reductant fluid not required (in some configurations)
Limitations	NO_x storage capacity is limited by physical size of LNT Highway and uphill driving can overwhelm the capacity of LNT, leading to high NO_x emission events For engines > 2.0 L, more frequent trap regeneration events are required, leading to additional fuel penalties (around 2%) Precious metal usage is high (approximately 10 to 12 g for a 2.0 L engine) NO_x adsorbers also adsorb sulfur oxides resulting from the fuel sulfur content, and thus require fuels with a very low sulfur content (< 10 ppm). Sulfur compounds are more difficult to desorb, so the system has to periodically run a short "desulfation" cycle	Limited NO_x conversion at low-load driving conditions (vanadium catalyst), sensitive to fuel sulfur content (copper-zeolite catalyst) For light-duty vehicles, exhaust temperature during urban driving conditions is usually below 200°C, whereas the vaporization of urea into ammonia requires an exhaust temperature of at least 180°C Requires additional urea distribution infrastructure (possibly periodic refills by user), on-board storage and heating, anti-tampering provisions, and injection systems (packaging constraints)	Most effective at low engine loads High real-world NO_x emissions during high load driving instances because the maximum applicable exhaust recirculation rate decreases with engine load Tradeoff between NO_x performance and fuel economy	High cost Packaging constraints (combined aftertreatment solutions take up more space than single-technology solutions) Calibration difficulties due to added complexity
Application examples	VW Polo, VW Golf, BMW 2-Series	Peugeot 308, Mercedes-Benz C200, Audi A5	Mazda 3, Mazda 6, Mazda CX-5	US market versions of BWM 3-Series, 5-Series and X5-Series

Table 4 - Overview of the main technologies for the control of NO_X emissions from Euro 6 Diesel passenger cars. (Taken from Yang et al., 2015).

Note: Cost estimates from Possada et al. (2012) "Estimated Cost of Emission Reduction Technologies for Light-Duty Vehicles". Variable geometry turbocharging is assumed for EGR.

DIESEL	PASSENGER CARS AND COMMERCIAL VEHICLES (M1, N1), MAX WEIGHT < 3500 KG				
	EURO 1 TO EURO 2	EURO 2 TO EURO 3	EURO 3 TO EURO 4	EURO 4 TO EURO 5	EURO 5 TO EURO 6
Regulated pollutants	HC+NO_x / PM / CO	NO_x / PM / CO / HC*	NO_x / PM / CO / HC*	NO_x / PM / CO / HC*	NO_x / PM / CO / HC*
Emissions target, g/km	0.7 / 0.08 / 1	0.5/ 0.05/ 0.64/ 0.06	0.25/ 0.025/ 0.5/ 0.05	0.18/ 0.005/ 0.5/ 0.05	0.08/0.0045/ 0.5/ 0.09
Emissions reduction	38% / 55% / %68	- / 37.5% / 36%/-	50% / 50% / 22%	28% / 80% / 0	66% / 10%/ 0
Base technology and comments	**Basic Euro 1:** • Fuel injection systems: based on Rotary or distributor pump. Fuel metering and timing are mech. operated. Fuel metering/timing variation was limited to specific load-speed conditions. • Mechanical or electrical fuel control • Indirect diesel injection (IDI) combustion • Low pressure injection (700-800 bar) • EGR based mostly on low-pressure mechanic operation	**Based on Euro 2 technology** • Some vehicles still use IDI (30% of PC market), mostly smaller diesel vehicles. Note: Elimination of first 40-second warm-up period during the test cycle (NEDC 2000) presents cold start challenges	**Based on Euro 3 technology** • DI becomes the standard technology	**Based on Euro 4 technology** Emission control heavily focused on: • Air-fuel management and combustion system improvements (R&D) • Engine tuning and mapping	**Based on Euro 5 technology** • PM control will likely follow the use of DOC + DPF. • NO_x control will depend highly on in-cylinder combustion and CO_2 emission requirements. Using SCR may be beneficial for large engines (Vd-3 liters) because the engine can be tuned for high FE and low PM emissions.
Engine -out emissions, A/F management	• ECU based control • Rotary/distributor pump with electronic assistance. • Electronically controlled IDI and DI incorporate solenoid-operated valves for improved fuel metering and timing. • Cooled EGR required in some vehicles.	• Rotary pump injection timing control improved (for cold start and fast idle) • Common-rail systems became available for Euro 3 vehicles. • DI comb+ high-pressure fuel injection (HPFI). • Pressure 900-1,300 bar • Cooled EGR. The EGR system is electronically operated and integrated with the ECU.	• High pressure fuel injection 1300-1600 bar • Air-fuel management and combustion system (nozzle, valves, piston, heads geometry) improvements (R&D) • Engine tuning and mapping • Four valves per cylinder • Turbocharging with intercooling • *Cooled EGR with DC motor actuator	• High pressure fuel injection 1600-1900 bar • Variable geometry turbo. (VGT) for improved air-fuel management for large vehicles. • Variable fuel injection timing for DPF active regeneration through injection delay • Variable valve timing (VVT) may also be used for DPF regeneration and improved FE	• High pressure fuel injection 1800-2100 bar • Dual loop, cooled EGR systems with motor actuator • Combustion research PCCI, LTC • Variable geometry turbocharger (VGT) may be used in most passenger cars and commercial vehicles. Improves fuel economy (FE)
Aftertreatment systems		• DOC for PM reduction (SOF fraction)	**Same as Euro 3** • Although not required for Euro 4 compliance, some vehicles were fitted with DPF in advance of Euro 5 regulations.	• DOC + DPF • DPF is regenerated through active or passive regeneration with high-temperature exhaust downstream the DOC and taking advantage of its NO_2 yield.	**Strongly depends on FE approach** • DOC+DPF+LNT • if 1.4 < Vd < 2.5 L • DOC+DPF+SCR • if Vd> 2.5-3.0L

Table 5 - Diesel technology requirements for control of conventional pollutants. EU regulations. (Taken from Posada et al., 2012)

3. Instruments for measuring NO_x during PTI

This section of the report summarises the instruments which are likely to be suitable for the measurement of NO_x during PTI, including the results of any studies in which the instruments have been tested and compared. The instruments were identified though a review of the literature and through the personal knowledge of the project members.

3.1. Chemiluminescence analyser

Although it is not used for PTI emission tests, the chemiluminescence analyser is the standard instrument for measuring NO and NO_2 in type approval tests (and also for ambient air quality measurements). It is also widely used as a reference method. The instrument detects the light emitted by electronically exited NO_2 molecules which are generated by the following reaction (Equation 9) between NO in the exhaust gas and ozone (O_3) which is added in a reaction chamber:

$$NO + O_3 \rightarrow NO_2 + O_2 + light$$

Equation 9: Reaction between NO in the exhaust gas and ozone O_3

The emitted light is measured with a photomultiplier sensor and is proportional to the NO concentration.

To enable NO_2 to be measured, the NO_2 resulting from the above reaction is reduced to NO inside the analyser using a converter at a high temperature. It is possible to measure NO and NO_x (NO plus NO_2 reduced to NO in the converter) by alternating the gas flow. Valves are used to pass the gas through the converter (for measurement of NO_x) or directly without the converter (for measurement of NO) to the reaction chamber. NO_2 is then calculated as difference between NO_x and NO. The ozone needed for the reaction is usually produced from oxygen within the analyser itself using an ozone generator.

3.2. Non-dispersive infrared absorption spectroscopy (NDIR)

Non-dispersive infrared absorption spectroscopy (NDIR) is based on the principle that when infrared light from a broadband source is passed through a measurement chamber, each gas present absorbs the light at a certain wavelength and in proportion to its concentration.

The remaining beam passes a filter to cut off other wavelengths and is detected by, for example, a pyroelectric sensor. Many different filter and detector technologies are used, including filter interference, gas-filter correlation, and pneumatic detectors.

NDIR is often used to measure CO, CO_2 and HC (usually calibrated as propane equivalents) as well as NO. However, the measurement of NO_2 is not possible as water vapour (from fuel combustion) absorbs at the same wavelengths, thus causing interference. It is therefore unlikely that NDIR will be suitable for use in PTI.

3.3. Non-dispersive ultraviolet absorption spectroscopy (NDUV)

The advantage of measuring NO and NO_2 in the ultraviolet region of the spectrum instead of in the infrared region is that there is no cross-sensitivity with water and CO_2.

Analysers which rely upon non-dispersive ultraviolet absorption spectroscopy (NDUV) have been used in portable emission measurement systems (PEMS) to measure on-road emissions of vehicles (*e.g.* for evaluating emission factors and models). These systems show a good correlation with the equipment used in the type approval procedure (Weiss *et al*., 2011).

However, NDUV instruments are currently rather expensive for PTI.

3.4. Electrochemical cells

A number of instruments based on electrochemical cells have been developed for use in PTI emission tests. In these instruments the oxidation of NO generates a small electric current, the magnitude of which is proportional to the amount of NO present. The fundamental principle involves the use of electrodes and a liquid or solid electrolyte. Variations include Na^+-conductor-based NO_x sensors (operated at about 150°C) developed in the 1980s, and a ZrO_2-based thick-film sensor (operated at 450°C) – known as a 'smart-NO_x' sensor – developed in the 1990s by NGK/VDO.

Electrochemical cells are relatively cheap, simple and robust, and can have a high selectivity, although some cross sensitivity with CO has been reported (Szabo and Dutta, 2003). Electrochemical sensors are usually classified as potentiometric (where the output is a voltage) or as amperometric (where the output is a current). Amperometric sensors also have a high sensitivity, and can be adjusted for the measurement of different gases by, for example, specifying chemical reactions in advance of the electrochemical reaction, modifying the diffusion barrier (porosity, pore distribution, *etc.*), or modifying the electrolyte, material and structure of the gas sensor (Vlad, 2008).

Various different types of electrochemical cell are available for use in gas sensors, but the fundamental principle is always based on electrodes and a liquid or solenoid electrolyte. Sensors typically consist of multi-layer ceramics and solid-state thick films.

3.5. Zirconia multilayer ceramics

Zirconia ceramic (ZrO_2): This type of ceramic is an oxide of zirconium (Zr), one of the rare earth metals. An important property of this ceramic is that it conducts oxygen ions when voltage is applied at high temperatures. Conversely, an electric current is generated when oxygen ions are mobile. This property can be put to practical use when zirconia is used in oxygen pumps and oxygen sensors and in fuel cell electrodes.

The use of the ceramics technology that has been developed to date, and by forming ZrO_2 into a proprietary two-chamber shape and using a multi-layered element, has enabled the development of a sensor to detect with high precision only those oxygen ions originating from nitric monoxide (NO) from among the oxygen ions present in the exhaust gas.

3.6. Fourier-transform infra-red spectroscopy (FTIR)

In FTIR the light from a broadband source transmitted through a scanning interferometer is measured as a function of the optical path length. The high signal-to-noise ratio of FTIR has led to its increasing use in laboratories. However, the interference of NO_2 measurement by water vapour remains. FTIR spectrometers are also significantly more complex than NDIR instruments.

3.7. Time response for NO_x emission measurement

On the website of Cambustion (www.cambustion.com) some application notes can be found. Cambustion was founded in 1987 by a research group at Cambridge University Engineering Department, to produce a fast response FID detector for HC measurement. They have applied their expertise and techniques from this fast FID detector to develop fast response measurement equipment of NO_x and CO & CO_2. The importance of a good time response for NO_x emission measurement was already highlighted in the TEDDIE study (CITA, 2011). The following figures show some difference in a quick and a conventional analyser.

Figure 7 shows both behaviours during an acceleration followed by a fuel cut. The difference in sample transport delay to both analysers is shown in Figure 8. The 2 millisecond time resolution of the fast analyser detects fast transients which are smeared out by slower analysers.

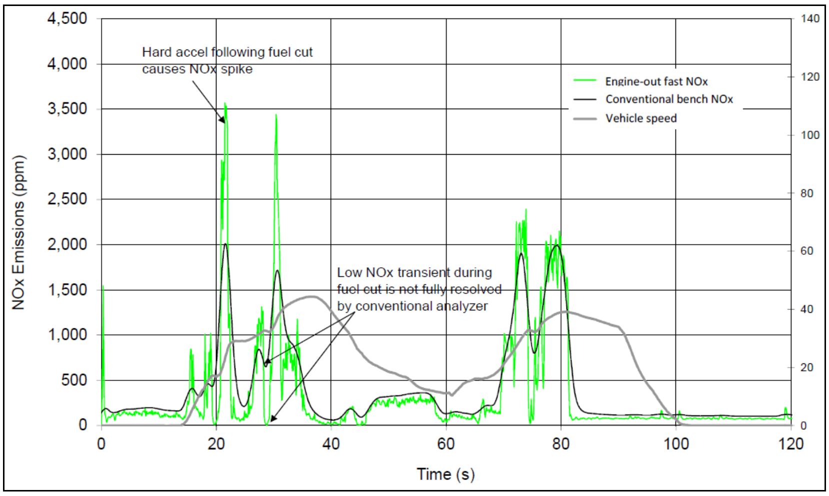


Figure 7 - Euro IV transient NO_X on WLPT cycle. (Taken from Cambustion Application Note CLD04v01, n.d. c)

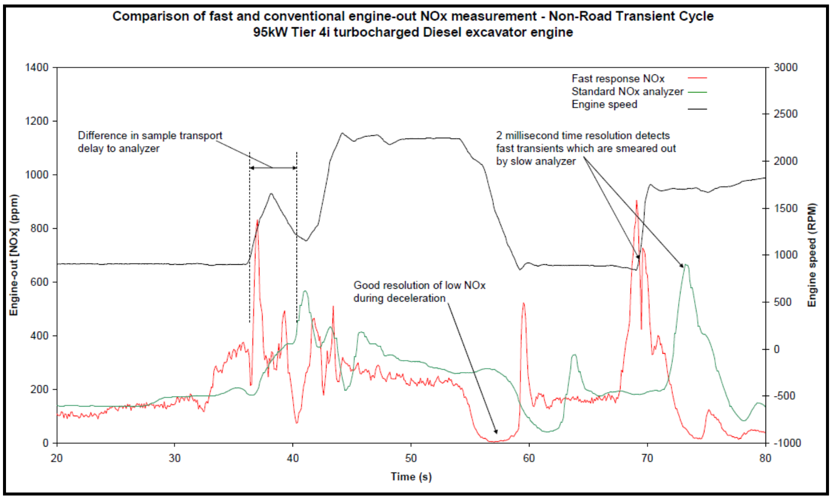


Figure 8 - Measurement of engine-out NO_x for transient SCR urea dosing accuracy. (Taken from Cambustion Application Note CLD02v01, n.d. a)

3.8. Review of existing equipment

Company name	Product name	Technology
ACTIA	Actigas AT505	Electrochemical
Automotive Test	P555	Electrochemical
AVL DiTEST	AVL DITEST CDS/MDS	Electrochemical
Bosch	BEA 050, 055, 060, with NO	Electrochemical
Brain Bee	AGS-688	Electrochemical
Capelec	CAP3050	Zirconia ceramic
MAHA	MET 6.3	Electrochemical + CCFET
SAXON-Junkalor	Infralyt ELD	Electrochemical
Sensors Inc.	SEMTECH-DS	NDUV
Sensors Inc.	SEMTECH-NO_X	NDUV
TEN	INNOVA 2800+NO_X	Electrochemical
TEXA	GASBOX AUTOPOWER	Electrochemical

Table 6 - Existing equipment

3.9. NDUV equipment

Sensors Inc. SEMTECH

An example of an instrument which uses the NDUV principle to measure NO and NO_2 is the SEMTECH-DS system manufactured by Sensors Inc. (Figure 9 -). The system is normally used in laboratory, such as for engine development. The SEMTECH-DS can be used to measure CO, CO_2, O_2, NO, NO_2 and THC in the raw exhaust from both spark ignition and compression ignition engines, and is compliant with the USEPA's CFR 1065 standard. There is an optional heated FID sampling probe which maintains the exhaust temperature at 191°C. Bespoke software is provided for controlling the SEMTECH-DS and calculating emissions. A wireless Ethernet connection can be used for communication between a computer and the instrument.

Figure 9 - Sensors Inc. SEMTECH-DS (reproduced by kind permission of Sensors Inc.).

3.10. Electrochemical equipment

Some examples of **electrochemical devices** are described below.

SAXON-Junkalor - Infralyt ELD

The Infralyt ELD instrument produced by SAXON-Junkalor GmbH is designed for the measurement of pollutant concentrations in diesel exhaust. It employs an infrared optical bench to measure CO, CO_2 and HC, and electrochemical cells to measure O_2, NO and NO_2. The Infralyt ELD is small, compact and easy to handle (Figure 10). The wide ranges available for measurement allow a diagnosis of modern diesel vehicles with DPFs. The instrument can be used with a small hand-held logging unit (with internal line printer) or with a PC/Notebook.

Figure 10 - SAXON-Junkalor Infralyt ELD (reproduced by kind permission of SAXON-Junkalor).

MAHA MET 6.3

The MET series is designed for the measurement of petrol and diesel vehicle exhaust during PTI. The MET 6.3 version is shown in Figure 11. Depending on the configuration, it can be used to measure the concentration of CO, CO_2, HC, O_2, NO_x, and particulate mass, as well as the turbidity coefficient.

The device is available in a version with a simple display (LCD), showing values and configurations, or with a graphical display and menu-driven operation. Communication to a PC system is via wireless (WLAN) or LAN. MAHA note that the instrument is easy to maintain, with filters being accessed through covers on the side of the body. The analyser is approved to the requirements of OIML Class 1.

Figure 11 - MAHA MET 6.3 (reproduced by kind permission of MAHA).

Autocal P550

The Autocal P550 is a small, light (5kg) instrument for analysing emissions (Figure 12 -) which is specifically designed for PTI emission checks. It employs NDIR to measure CO, CO_2, and HC, and electrochemical cells to measure O_2 and NO. The P550 also measures oil temperature, and displays engine speed and (calculated) lambda. The instrument works independently (*i.e.* it does not require an external computer), and has its own LCD screen. The analyser is approved to the requirements of OIML Class 1.

Figure 12 - Autocal P550 (reproduced by kind permission of Autocal).

3.11. Zirconia multilayers ceramic equipment

CAP3600 Equipment

Hardware :

Capelec is providing, in order to perform the test campaign:

- A CAP3600 Equipment (PC interface, touch screen, data storage, tests printing)
  - CAP3050 : OpaciNO_X : combined unit with opacity and NO_x measurement (Zirconium technology)
  - CAP4250 : EOBD data acquisition, used in addition with tail pipe measurement
  - Customised software with automatic and guided procedure (test data gathering and storage)
  - LAN connexion with remote control for maintenance, update and test result data transfer.

Figure 13 - CAP3600 (reproduced by kind permission of Capelec).

Data measurement

NO_X: provided via CAP3050, response time <1s
RPM: provided via CAP4250 (live data) and EOBD plug
Engine filling ratio (p): computed from live EOBD data and vehicle's data info (cylinder capacity)
Opacity: Pic record via CAP3050
OBD & EOBD data: DTC, Readiness tests and readiness status, MIL status, EGR info (command, position feedback)

Opacity	NO_x
▪ Dynamic Precision : 0.05m-1 ▪ Zero Precision : < 0.005m-1 ▪ Static Precision +/-0.5% (filter) ▪ Resolution : 0.001m-1 or 0.01%	▪ Range 0 to 5000 ppm ▪ Precision : ○ +/-15ppm (0 to 1000 ppm) ○ 1.5% from 1000 to 5000ppm ▪ Response time (1s)

	Instrument 1	Instrument 2	Instrument 3	Instrument 4	Instrument 5	Instrument 6	Instrument 7	Instrument 8	Instrument 9	Instrument 10	Instrument 11	Instrument 12
Company name	MAHA	Sensors Inc.	Sensors Inc.	SAXON-Junkalor	Capelec	Robert Bosch	Brain Bee	Automotive Test	AVL DiTEST	ACTIA	TEN	TEXA
Product name	MET 6.3	SEMTECH NO_x	SEMTECH-DS	Infralyt ELD	CAP3050	BEA 060 , BEA 055	AGS-688	P550	AVL DITEST MDS/CDS	AT505	INNOVA 2800+NO_x	GASBOX AUTOPOWER
Parameters	NO, NO_2 (O_2, CO, CO_2, HC)	NO, NO_2	NO, NO_2, O_2, CO, CO_2, HC	NO, NO_2 (O_2, CO, CO_2, HC)	$NO_x^{(a)}$	NO, O_2, CO, CO_2, HC	NO	NO	NO, CO, CO2, HC, O2	NO, NO_2 (O_2, CO, CO_2, HC)	NO, NO_2 (O_2, CO, CO_2, HC)	NO (O2, CO, CO2, HC)
Measurement method(s) for NO and/or NO_2	NO: electro-chemical NO_2: CCFET[2]	NDUV	NDUV	Electro-chemical	Zirconia ceramic	NO: electro-chemical	NO: electro-chemical	NO: Solid State NO2 Solid State CO, CO2, O2 Particulate	NO: Electro-chemical	Electrochemical	Electro-chemical	NO: electro-chemical
Range	**NO:** 0-5,000 ppm **NO2:** 0-500 ppm	**NO:** 0-3,000 ppm **NO2:** 0-500 ppm	**NO**: 0-2500 ppm **NO2:** 0-500 ppm	**NO**: 0-2,000 ppm **NO2:** 0-500 ppm	NO_x: Range: 0 – 5000ppm **O2:** Range:0-25%	**NO:** 0-5,000 ppm	**NO**: 0-5,000 ppm, resolution: 1 ppm	**NO:** 0-4,995 ppm	**NO:** 0-5,000 ppm	**NO:** 0-5,000 ppm **NO2:** 0-500 ppm	**NO:** 0-5,000 ppm resolution 1 ppm	**NO:** 0-5.000 ppm (res. 1 ppm)
Accuracy	NO: 32-120 ppm NO_2: 32-120 ppm	N/A	NO: ±3% of reading or ±15 ppm NO_2: ±3% of reading or ±10 ppm	NO: ±5% NO_2: ±5%	NO_x: ± 15ppm (0 to 1000) ± 1,5% from 1000 **O2:** Precision:	4% 0-4000 ppm +-25ppm 8% 4000-5000ppm	N/A	N/A	NO: ± 5ppm Or ± 1% o.M.	NO: ±3% of full scale NO_2: N/A	Range 0…4000 ppm ± 4% or 25 ppm Range 4000-5000	

[2] CCFET = Capacitive-Coupled Field-Effect Transistor

	Instrument 1	Instrument 2	Instrument 3	Instrument 4	Instrument 5	Instrument 6	Instrument 7	Instrument 8	Instrument 9	Instrument 10	Instrument 11	Instrument 12
Company name	MAHA	Sensors Inc.	Sensors Inc.	SAXON-Junkalor	Capelec	Robert Bosch	Brain Bee	Automotive Test	AVL DiTEST	ACTIA	TEN	TEXA
					±0,4% around 0 ± 0,8% on the range						ppm ± 8%	
Calibration interval	1 year	3-6 months	3-6 months	1 year	6 months	6 months	1 year	6 months	3 months	6 months	1 year	1 year
Weight	5 kg	13 kg	35.4 kg	9 kg	500 g (bench)	9 kg	5 kg	5 kg	2,2 kg	6 kg	15 kg	6 kg
Dimensions: length x height x width (cm)	40.6 x 22.5 x 16.0	30.8 x 13.6 x 43.6	55 x 36 x 43	29.4 x 23.8 x 35.5	13 x 7 x 7	41.4 x 33.0 x 28.0	43.4 x 19.0 x 29.1	29.0 x 14.0 x 18.0	344 x 252 x 85mm	N/A		46 x 27 x 24
Data interface available	USB	CAN, RS232, Ethernet, USB. Options available.	Wireless	RS232, USB. Bluetooth , Adapter available	RS232, USB, Bluetooth	USB, Bluetooth	USB, RS232, Bluetooth.	RS232. Data logging optional extra	BT, USB	RS232, USB	RS232	RS232, BLUETOOTH
Cost per unit				7.175,-- Euro net EXW (list-price)		€ 3700 stand-alone	4750€+IVA With NO_x and Diesel special probe included					€ 3.360

	Instrument 1	Instrument 2	Instrument 3	Instrument 4	Instrument 5	Instrument 6	Instrument 7	Instrument 8	Instrument 9	Instrument 10	Instrument 11	Instrument 12
Company name	MAHA	Sensors Inc.	Sensors Inc.	SAXON-Junkalor	Capelec	Robert Bosch	Brain Bee	Automotive Test	AVL DiTEST	ACTIA	TEN	TEXA
Time per test				T90- ca. 20 seconds	Reaction time < 1s Procedure : 60s	Depending on test procedure						
Covering Petrol and/or Diesel vehicles?				Petrol and Diesel vehicles	Diesel vehicles	Covers both Diesel and petrol vehicles	Petrol (with standard probe)and Diesel (with special probe)				Petrol and diesel after Euro4	Petrol (and also diesel)
Are you ready to participate to the CITA Set II Study?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Depending on time scale	Yes	Yes	Yes	Yes
Procedure dedicated to NO_x	Yes Dynamic (roller)	No	No	No	Yes Static		No	No	Yes Static	No	No	No

Table 7 - overview specifications NO_X equipment

4. PTI test procedures for the test of diesel vehicles involving NO_X measeurements

4.1. Test procedures disclosed in the TEDDIE-study

This part is integral taken from the CITA TEDDIE study (CITA, 2011). Note that the references in this annex are not necessary duplicated in the reference list of this study (unless they are used in the study itself).

4.1.1. Unloaded tests

Idle tests

Idle tests are commonly used for petrol vehicles in I/M programmes. One-stage tests with the engine at natural idle are the most common, but there are some examples of two-stage tests in which emissions are measured at both low and high engine speed. The inclusion of a lambda test at high idle can help to reveal whether the catalytic converter is functioning, the exhaust pipe is leaking, and the testing has been carried out properly (USAID, 2004).
The test can last from less than one minute in the case of a one-stage test without pre-conditioning to about 10 minutes in the case of a two-stage test with pre-conditioning.
Idle tests are not considered to be appropriate for modern diesel vehicles, as NO_x and PM emissions under no-load conditions are low.

Free acceleration smoke (FAS) test

In many countries the PTI emission test for all types of diesel vehicle involves the measurement of exhaust smoke opacity. Because smoke levels at engine idling speed (or under low load) are nearly always low regardless of the condition of the vehicle, free acceleration tests are often used (Faiz *et al.*, 1996). For example:

- In Europe, Directive 72/306/EEC describes the FAS test which is performed as part of the type approval procedure. This procedure is also used for PTI testing, as specified in Directives 2009/40/EC and 2010/48/EC.

- In the United States the EPA recommends (but does not mandate) the use of the free acceleration test described in SAE J1667 as the basis for diesel vehicle inspection. SAE refers to the test as a 'snap-acceleration procedure', but it is also commonly called the 'snap-idle test', the 'J1667 test' and the 'free-acceleration test'. Several jurisdictions have either implemented such tests or have pilot programmes under way.

The particular test procedures used are in all cases similar, though not identical. The test is typically performed as described earlier for the EU case. Some of the advantages disadvantages of the FAS test were also discussed earlier.

INCOLL/AUTONAT

These two tests were designed for use with petrol cars. The INCOLL test was devised by the University of Technology of Gothenburg. A similar test called AUTONAT has also been proposed by the Centre de Recherche en Machine Thérmiques in France. The tests were described by Samaras and Zachariadis (1995).

Neither the INCOLL nor the AUTONAT tests require the use of a chassis dynamometer. Instead, the vehicle's engine is accelerated and decelerated rapidly so that the load the engine has to overcome in order to accelerate its rotating and reciprocating parts (including flywheel and gearbox) approximates to the load during a normal driving cycle.

The INCOLL test involves increasing the engine speed from low idle to 4,500 rpm in less than 100 ms. In the AUTONAT test the accelerator pedal is actuated according to a driving schedule through an electronically controlled mechanism, while either the raw exhaust concentrations are continuously measured or diluted exhaust is collected and analysed after the end of the test.

Both the INCOLL and AUTONAT tests have demonstrated reasonably good correlation with emissions over type approval cycles. Whilst the conduct of the actual test cycle requires between only two and five minutes, it takes some time (around 30 minutes in the case of AUTONAT) to obtain the relationship between accelerator pedal position and engine speed and load for each car type. This approach is therefore considerably more complicated than applying a standard test to all vehicle types.

Procedures described by Norris (2005)

In the UK Low-Emission Diesel Research project a gentle acceleration was used (Norris, 2005). The study showed that during gentle accelerations EGR systems operate in different ways. To ensure that the test included a working region of the EGR the engine speed was slowly increased from idle to a suitable upper limit (4,000 rpm), with the vehicle unloaded (*i.e.* neutral gear selected). The rate of increase in the engine speed was not described, but a slope of 50 rpm per second would appear to be reasonable. We refer to this test hereafter as 'Norris-A'. Since the EGR unit is an important emission-reduction system for NO_x emissions, this could be an important test. In the study itself the working of the EGR was determined using concentrations of CO_2 and O_2.

In the same study another test cycle was used in order to turn on the EGR. For some of the vehicles tested merely gently touching the accelerator pedal at idle (up to 900-1000 rpm) caused the EGR unit to turn on, and then after a certain time (2 minutes) to turn off again. We refer to this test hereafter as 'Norris-B'. This procedure was not applicable to all vehicles.

4.1.2. Loaded steady-state tests

These are the simplest loaded tests, in which the engine is held at a specified speed (or a series of sequential speeds) for a desired amount of time by the variable brake loading provided by a power-absorbing dynamometer. In the steady state no inertia simulation is necessary: the load on the engine stays the same. The application of load permits the measurement of NO_x.

US Federal 3-Mode

The Federal 3-Mode test was developed in the United States in the 1970s as a possible short procedure for evaluating emissions from petrol cars in I/M programmes. The vehicle is placed on a dynamometer without a flywheel. The test involves two different vehicle speed/load points (**Error! Reference source not found.**7) and a low idle (unloaded) point. The load varies according to the vehicle's inertia weight. The whole test takes around 10 minutes to complete (including preparation, testing and documentation). The engine needs to be preconditioned for 10-15 seconds at 2,500 rpm. Each test phase can then take no longer than two minutes.

Inertia [kg]	High speed		Low speed	
	Speed [km/h]	Load [kW]	Speed [km/h]	Load [kW]
≤ 1134	80.00	15.75	50.00	6.75
1135 - 1586	80.00	19.50	50.00	9.00
1589 - 2041	80.00	23.25	50.00	11.25
≥ 2041	80.00	27.00	50.00	13.50

Table 8 - US Federal 3-Mode test – loaded points

Pollutant concentrations (CO, HC and NO_x) are measured in the raw exhaust. NDIR analysers are used for CO and HC, and a chemiluminescence analyser for NO_x. Whilst the results from the test correlated reasonably well with those from the Federal Test Procedure (FTP) used for type approval in the US, it was never implemented due to the high capital costs associated with the dynamometer and NO_x analyser (Norris, 2002).

Clayton Key Mode

Like the Federal 3-Mode test, the Clayton Key Mode test was developed in the United States in the 1970s for the testing of petrol cars. The test itself is also very similar to the 3-Mode test, the main differences being the actual vehicle weight band and the speed/load points used (**Error! Reference source not found.**8). Correlations with FTP test results were good, but again the test was not implemented because of high capital costs. Poor repeatability of the test was also a factor.

Inertia [kg]	High speed		Low speed	
	Speed [km/h]	Load [kW]	Speed [km/h]	Load [kW]
≤ 1270	60.00	10.50	47.00	3.75
1271 - 1724	72.00	16.88	50.00	6.75
≥ 1725	80.00	21.38	53.00	8.25

Table 9 - Clayton Key Mode test

CalVIP

The CalVIP test was developed by the California Air Resources Board (CARB) and was used in the centralised I/M programmes that ran in Los Angeles from 1979 to 1984. Few details of the test appear to be available. It is again very similar to the US Federal 3-Mode test, but with different speed and load points (**Error! Reference source not found.**9).

Number of cylinders	Speed [km/h]	Load [kW]
≤ 4	65.00	7.500
5 up to 6	65.00	11.250
≥ 7 and m ≤ 1477 kg	65.00	13.125
≥ 7 and m > 1477 kg	65.00	15.375

Table 10 – CalVIP test

Samaras and Zachariadis (1995) stated that it would be reasonable to assume that either a brief operation at 2,500 rpm (as in the Federal 3-Mode and Clayton Key Mode tests) or a 3-minute steady-state loaded operation on a dynamometer (as in transient loaded tests) would be used for preconditioning purposes.

D550

The D550 short steady-state test is described by Anyon (1995). It is conducted using a constant dynamometer load equivalent to a fully laden vehicle driving up a 5% gradient at 50 km/h (Figure 14). This represents a near full-load condition for most vehicles. As it is a constant load, constant-speed test, it requires only a simple dynamometer. The test is designed so that there is no need to establish maximum power or torque outputs.

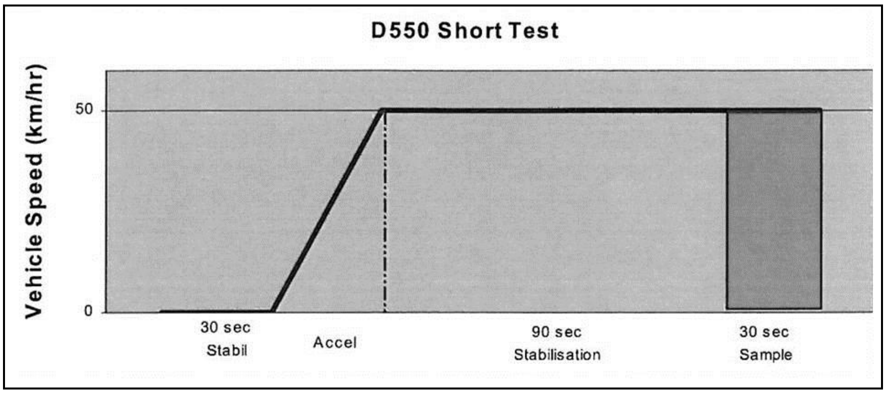


Figure 14 - D550 test (Kolominskas et al., 2005).

Acceleration Simulation Mode (ASM) tests

In the ASM test for petrol cars the vehicle is driven on a basic chassis dynamometer without the use of inertial flywheels. The inertial load normally encountered during accelerations is simulated by applying additional load. The vehicle is driven on the dynamometer at a constant speed, with a steady-state power absorption that is equal to the actual road load of the car (except the rolling resistance) during acceleration. This circumvents the need for flywheels. However, at high speed / high acceleration combinations the required power absorption is too great to be achieved without the engine overheating. This restricts the useable speed/power range.

The US state of Texas has introduced the ASM test for I/M. Detailed procedures are available from the Texas Department of Public Safety (De la Torre Klausmeier Consulting Inc., 2002). In the Texas ASM test HC, CO and NO_x are measured during two modes: a high load / low speed condition (the 5015 test) and a moderate speed / moderate load condition (the 25/25 test):

- The ASM 5015 tests a vehicle at a load simulating 50% of the maximum acceleration rate on the FTP (50% of 3.3 mph s^{-1}) and 15 mph.

- The ASM 2525 tests a vehicle at a load simulating 25% of the maximum acceleration rate on the FTP (25% of 3.3 mph s^{-1}) and 25 mph.

The ASM test is more effective at identifying emission-related problems than the two-speed idle test which was previously used in Texas, and it is much more difficult to get a vehicle to pass it without performing necessary repairs. An evaluation study of ASM tests concluded that they can identify more than 80% of excess HC and CO emitters, with few errors of commission (Austin and Heirigs, 1995).

In the late 1980s the association of German TÜV also investigated the ASM principle for both diesel and petrol cars. In this variant the car was driven at a nominal speed and full load, and then at 45% of the nominal speed and full load. Two smoke measurements were taken at each condition. The study concluded that the test was more appropriate than a no-load test for characterising the emission behaviour of diesel cars. However, it was not legally enforced in Germany because the EC-wide free acceleration test was considered at the time to be satisfactory (Norris, 2002).

The ASM2050 cycle focuses on the urban part of driving cycles, as urban transport emissions in particular are at the forefront of public and political debate. The driven speeds are therefore between 0 and 50 km / h. The two constant speed points are at 20 and 50 km / h.

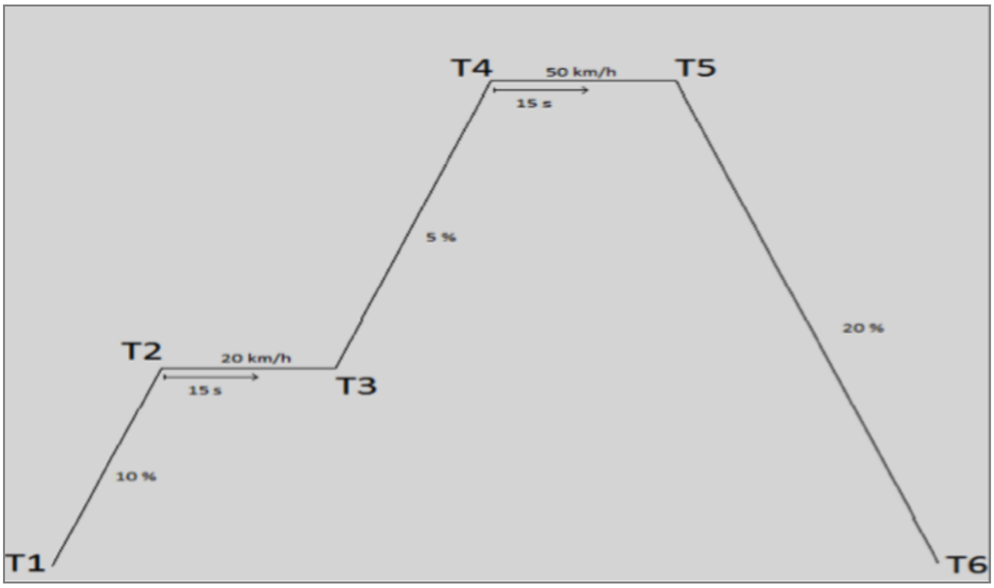


Figure 15 – ASM2050 test.

There are two variants of the ASM2050. Both are the same and are shown in Figure 15. In variant 1, the cycle is driven from the point T2 in regularly second gear to end in variant 2 is switched at the point T4 from second gear to third gear and thus the 50 km / h in third gear driven (Pando, 2016).
The following describes the process of both variants in more detail:

Variant 1 (ride in first and second gear):

- T1 to T2: acceleration in first gear with 10% load specification to 20 km / h in 4 seconds.
- T2: gear change from first gear to second gear.
- T2 after T3: Constant driving at 20 km / h in second gear for 15 seconds.
- T3 to T4: acceleration in second gear with 5% load specification to 50 km / h in 4 seconds.
- T4 to T5: Constant travel at 50 km / h in second gear for 15 seconds.
- T5 to T6: braking to standstill.

Variant 2 (ride in first, second and third gear):

- T1 to T2: acceleration in first gear with 10% load specification to 20 km / h in 4 seconds.
- T2: gear change from first gear to second gear.
- T2 after T3: Constant driving at 20 km / h in second gear for 15 seconds.
- T3 to T4: acceleration in second gear with 5% load specification to 50 km / h in 4 seconds.
- T4: gear change from second to third gear.
- T4 to T5: Constant travel at 50 km / h in third gear for 15 seconds.
- T5 to T6: braking to standstill

'Lug-down' test

The lug-down test is a basic loaded test which has been used in some countries, including the United States and Hong Kong. The vehicle is operated on a chassis dynamometer at a fixed speed while the dynamometer load is increased to the point where the vehicle is running at full throttle. The dynamometer load is then gradually increased to reduce the engine speed until the engine is labouring or 'lugging'.

The International Standards Organisation specifies a test method (ISO 7644) for measuring opacity using a dynamometer-based lug-down test.

Colorado has introduced dynamometer lug down tests which, for heavy-duty diesel vehicles, are contained in Regulation 12, Part A.IV.C.4 and Part B.III.C.4.b (Colorado Department of Public Health and Environment, 2006). In this test, the vehicle is run on the dynamometer at wide-open throttle during the following sequence:

(1) The vehicle is run at no load and at maximum engine speed in a gear that produces a road speed between 60 and 70 mph (or the maximum that can be obtained).

(2) Load is applied to bring the engine to its rated speed and held for 10 seconds while opacity is measured.

(3) Load is applied to lug the engine to 90%, 80% and then 70% of rated speed, pausing at each speed for 10 seconds while opacity is measured.

The maximum smoke opacity is then compared with the standard. NO_x measurements could also be taken during the test.

The above procedure is not to be confused with the one of the same name which has previously investigated in the UK. In this case the vehicle is placed on inexpensive unloaded free rollers, and full throttle is applied to drive the road wheels to a reasonable operating speed in gear, with the vehicle's brakes being used to apply load to the engine. However, the use of the vehicle brakes to apply load whilst the vehicle is driven on free rollers may be considered to have safety implications and also has a tendency to cause tyre damage. Moreover, the test provides no information on engine load, although this could be inferred from OBD (McCrae *et al.*, 2005; Latham, 2007).

Pennsylvania § 169.5 smoke test cycle

A smoke emissions test is specified in the provisions of The Pennsylvania Code[3]. The test is conducted according to the following sequence (The Pennsylvania Code, 1977):

(1) *Idle mode.* The engine is kept at idle for 1.5 to 2 minutes at the recommended low idle speed of the manufacturer. The dynamometer controls are set to provide minimum load by turning the load switch to the 'off' position or by adjusting the controls to the minimum load position.

(2) *Acceleration mode.* This proceeds as follows:

- The engine is accelerated at full throttle against inertia, or alternatively against a pre-programmed dynamometer load, such that the engine speed increases to 85-90% of rated speed in 3.5 to 5.5 seconds. For maximum repeatability on turbocharged engines with more than 1.5 pressure ratio, this should be held to closer limits. The acceleration should be kept linear within plus or minus 100 rpm.

- When the engine reaches 85-90% of the rated speed the throttle is closed rapidly and any dynamometer load is removed.

- Based on a pre-set load, the engine speed is allowed to drop to the intermediate speed within plus or minus 100 rpm.

- Full throttle is then applied and the engine speed is increased against a dynamometer load schedule such that the engine speed reaches 95-100% of the rated speed in 10±2 seconds.

(3) *Rated speed mode.* This involves the following steps:

- Proceeding from the acceleration mode, the dynamometer controls are adjusted to permit the engine to develop full-load power at the rated speed.

- The engine is allowed to operate for one minute after the load and speed have stabilised at full-load power at rated speed.

(4) *Lugging mode.* Here, the dynamometer controls are adjusted without changing the throttle position to slow the engine gradually to the intermediate speed. This engine lugging operation is performed smoothly over a period of 35±5, seconds. The slowing rate of the engine is kept linear within plus or minus 100 rpm.

[3] Title 67 Transportation, § 169 Diesel smoke measurement procedure.

(5) *Intermediate speed mode.* The engine is allowed to operate at full power at the intermediate speed for one minute after the load and speed have stabilised.

(6) *Engine unloading.* After completion of the lugging and intermediate speed modes the dynamometer and engine are returned to the idle condition. The zero and span of the smoke opacimeter may be checked and reset if necessary. If either zero or span drift is in excess of 2% the test results are considered to be invalid.

4.1.3. Loaded transient tests

In loaded transient tests the engine power and speed are varied throughout the test cycle. Different test cycles are used in different jurisdictions, and some of them are used in I/M programmes. It has been noted that for diesel vehicles transient testing eliminates the risk of engine damage associated with unloaded tests (McCrae *et al*., 2005).

HOT EUDC test

The HOT EUDC test was used during the Second CITA Programme on Emission Testing at Periodic and Other Inspections (CITA, 2002a). The test is derived from the New European Drive Cycle (NEDC), or 'Type I' test, which is used for the type approval on new car and light-duty vehicle models in the EU, as outlined in Annex III of Directive 70/220/EEC.

The NEDC test consists of two phases: an Urban Driving Cycle (UDC) consisting of a series of accelerations, steady speeds, decelerations and idling, and an Extra-Urban Driving Cycle (EUDC) which is run immediately after the UDC. The latter consists of roughly half steady-speed driving (at 75-120 km/h) and half accelerations/decelerations and a little idling. The test is undertaken on a vehicle which has been left to soak at between 20°C and 30°C for at least 6 hours, and until the engine oil and coolant temperatures are within ± 2°C of the ambient temperature.

The duration of the NEDC is 1,180 seconds for Euro III vehicles and later, with the UDC and EUDC phases being 780 seconds and 400 seconds long respectively. The Euro III test differs from the Euro II and earlier certification procedure (specified in directive 98/69/EC), in that the earlier test included a 40-second idling period that preceded the start of emissions sampling.

However, key aspects of this cycle which make it unattractive for I/M testing are:

- It is a cold-start test, requiring at least a 6 hour pre-run soak.
- Its long duration.
- The requirement for a dynamometer with full inertia simulation.
- The specification of a full-flow dilution tunnel and emission-measurement system.
- The high specification of the analysers.

Even if raw exhaust measurements were made, the first three of these aspects render this test impractical for I/M programmes.

In the CITA Hot EUDC test the operating cycle consists of the EUDC only. The dynamometer inertia is set at the manufacturer's value or according to the Directive, and following sequence is applied:

(1) *First Type I test.* The exhaust gases are measured during the complete cycle and during the second part. A four-gas test and an EOBD test are also carried out.

(2) *HOT EUDC cycles.* One or more faults are introduced. During the driving cycle the fault should be detected by the EOBD system. After the driving cycle (a HOT EUDC test) the four-gas test and an EOBD test are conducted. The HOT EUDC cycles are started with the engine running at the same speed and the engine oil at the temperature reached during the Type I test. The HOT EUDC tests are repeated after each failure in a series of one or more failures. When the whole failure series for the vehicle has been completed, the emissions during the HOT EUDC test are compared with the results from the measurements of the vehicle with faults to decide which fault setting will be measured during a second complete Type I test.

(3) *Second Type I test.* After the series of HOT EUDC cycles, a supplementary Type I test is conducted. During this phase the four-gas test and an EOBD test are also carried out. There will therefore be at least two Type I results for each series of HOT EUDC tests.

DT80 and DT60 tests

The DT80 procedure, which is applicable to diesel vehicles in Australia, is an aggressive, mixed-mode test with three full-load accelerations to 80 km/h, followed by a steady-state 80 km/h cruise (Brown *et al.*, 1999). This test has been designed to evaluate vehicle emissions during typical 'real-world' operating modes and conditions, and requires the use of a dynamometer with inertia simulation.

The Australian National Transport Commission described the DT80 procedure for testing of diesel exhaust emissions as follows (National Transport Commission, 2006):

(1) Idle for 60 seconds.
(2) Accelerate rapidly to 80 km/h under simulated inertia.
(3) Decelerate and gently applying brakes to bring the vehicle to a standstill.
(4) Idle for 10 seconds.
(5) Accelerate rapidly to 80 km/h under simulated inertia.
(6) Decelerate and gently applying brakes to bring the vehicle to a standstill.
(7) Idle for 10 seconds.
(8) Accelerate rapidly to 80 km/h under simulated inertia.
(9) Maintain speed at 80 km/h for 60 seconds.

Figure 16 - DT80 (indicative graph): Speed [km/h] as a function of time [s](Vyt, 2008).A2 shows the modes of operation. The actual test will result in a graph that has more variation than the indicative graph, because of the need to change gears when accelerating. The driver selects the most appropriate gear-change points for the vehicle being tested to achieve the correct speed.

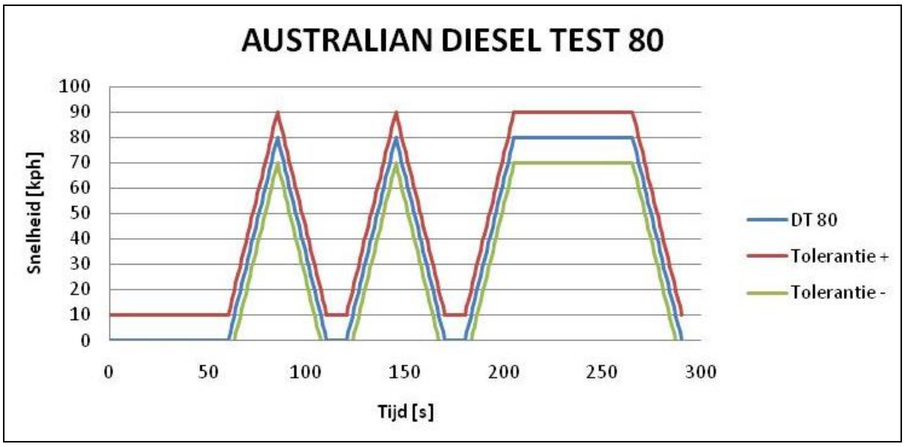


Figure 16 - DT80 (indicative graph): Speed [km/h] as a function of time [s](Vyt, 2008).

The DT60 is a shorter, aggressive, mixed-mode test which is very similar to the DT80. It has two full-load accelerations to 60 km/h, followed by a steady-state 60 km/h cruise (Figure 17 – DT60 (indicative graph): Speed [km/h] as a function of time [s](Vyt, 2008).

17). This test again requires the use of a dynamometer with inertia simulation.

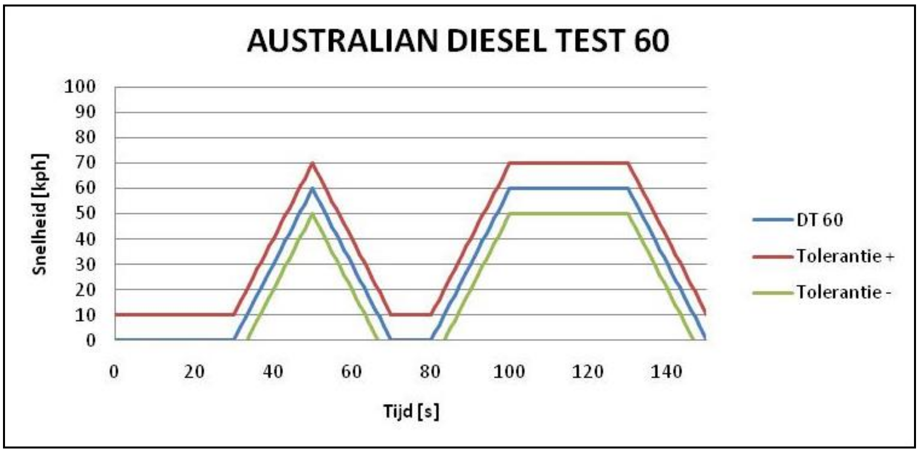


Figure 17 – DT60 (indicative graph): Speed [km/h] as a function of time [s](Vyt, 2008).

AC5080

The AC5080 is a short I/M test proposed by Parsons Australia Pty Ltd for CARB (Figure 18 - AC5080 simplified indicative graph: Speed [km/h] as a function of time [s](Vyt, 2008).

18). It is a mixed-mode test which begins with a 10-second idle followed by a wide-open throttle acceleration to 50 km/h, a steady-state cruise at 50 km/for 60 seconds, a wide-open throttle acceleration to 80 km/h, and finally a steady-state cruise at 80 km/h for 60 seconds.

It is less aggressive than the DT80, but according to Parsons it may be more representative of on-road driving. As with the DT80 and DT60 it requires the use of an inertia simulating dynamometer. Since the time taken to reach 50km/h and 80km/h is vehicle- and load-dependent, the speed-time profile varies.

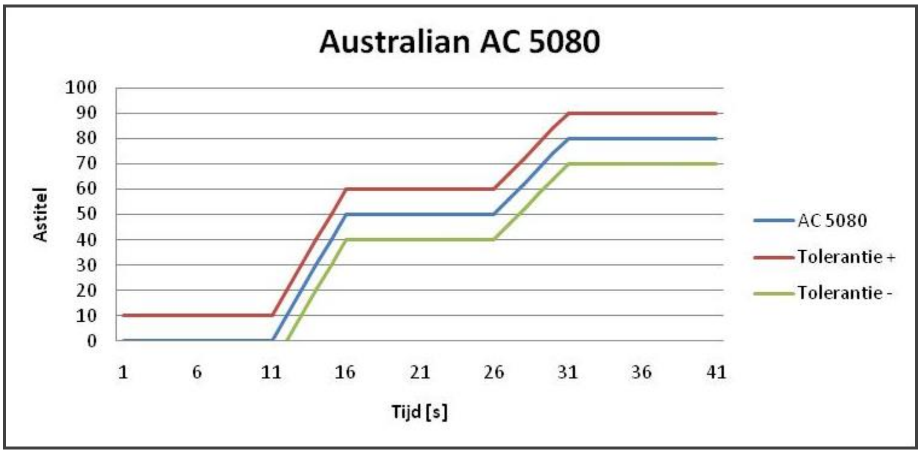


Figure 18 - AC5080 simplified indicative graph: Speed [km/h] as a function of time [s](Vyt, 2008).

IM 240

The IM240 test was developed by the USEPA as an enhanced in-service emission test for light-duty vehicles, and is used in I/M programmes in a number of states. Under this procedure a vehicle is mounted on a dynamometer with associated flywheels - thus allowing the simulation of the vehicle inertia - and is driven over a transient cycle. The name of the test relates to its duration (240 seconds). It is a condensed version of the FTP-75 test; the first 240 seconds of the FTP are taken as the basis for the IM240.

The test cycle is shown in Figure 19 - IM240 simplified indicative graph: Speed [km/h] as a function of time [s](Vyt, 2008).

19). The test cycle represents a 1.96 mile (3.1 km) trip with an average speed of 29.4 mph (47.3 km/h) and a maximum speed of 56.7 mph (91.2 km/h).

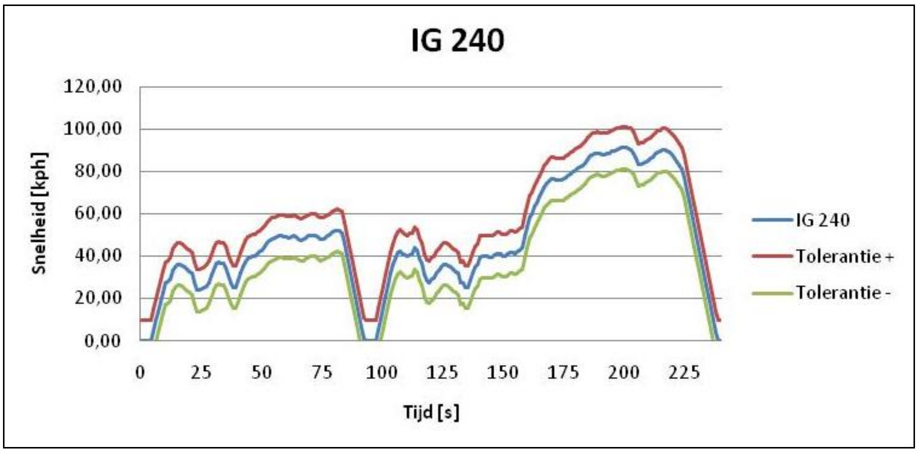


Figure 19 - IM240 simplified indicative graph: Speed [km/h] as a function of time [s](Vyt, 2008).

The IM240 procedure also incorporates a constant volume sampling system and gas analysers, as used in the full FTP-75 (Pidgeon and Dobie, 1991; EPA, 2000). There is an alternative version of the IM240 test - known as IG240 - which utilises less expensive inspection-grade equipment. Like the IM240, it is a transient test but is designed primarily for use in a decentralised programme.

The advantage of this method is that it allows a more realistic simulation of real-world driving conditions, but the testing time and capital costs are far greater than for simple idle tests. The in-service IM240 has been found to show good correlation with the FTP-75 for CO_2 and NO_x but poor correlation with CO and HC (McCrae e*t. al.,* 2005).

Oregon Bureau of Automotive Repair test (BAR31)

The BAR31 is a short, loaded dynamometer test used in some US states, primarily for measuring diesel opacity, but gaseous pollutants are also measured in some cases. The test uses similar equipment to the IM240, although the driving cycle has been truncated to 31 seconds, with the vehicle sharply accelerating and decelerating through the test. A vehicle is allowed three chances to pass the test before a failure is registered (McCrae e*t. al.,* 2005).

CDH-226

One of the earliest short tests was the CDH-226 driving schedule, developed by the Colorado Department of Health. The driving cycle lasts for 226 seconds, and the total test duration is about 10 minutes. This short cycle was developed specifically for vehicles equipped with a three-way catalyst, and is aimed at achieving high correlation with the FTP.

The CDH-226 is a ‘smooth’ cycle which requires relatively little throttle action. Throttle action is an important variable affecting vehicle emissions, and could be important in identifying malfunctioning vehicles. For these reasons, EPA decided to develop a more transient alternative to the CDH-226, and the result was the IM240 (Pidgeon and Dobie, 1991).

4.1.4. PTI tests for diesel vehicles

The PTI tests for diesel vehicles in non-EU countries are summarised in table A5.

This information was taken partly from the questionnaire responses and partly from the existing literature. Whilst an attempt has been made to obtain current information, it is possible that some of the test details taken from the literature are now out of date and ought to be confirmed.

Country	Exhaust components measured [1]	Chassis Dyno?	Test	Source[2]
Australia	NO_x, PM, Opacity	Yes	DT80, DT60	BIVV
Bangladesh	HSU	-	-	ADB
Brazil, Parana State	N/A	-	Free Acceleration	Questionnaire
Cambodia	HSU	-	-	ADB
Canada, Ontario	Opacity	-	Free Acceleration	Sierra
Canada, Vancouver	Opacity	Yes	Free Acceleration	Sierra
China, Beijing	Opacity, HC, CO, NO_x	-	Free Acceleration	Sierra
China, Hong Kong	Opacity	Yes	Lug-down	Sierra
China, Hong Kong	HSU	-	Free acceleration	BIVV
China, Hong Kong	HSU	-	Loaded lug-down	BIVV
Colombia	HSU?	-	N/A	Questionnaire
India	HSU	-	Free Acceleration	ADB
Indonesia	HSU	-	Free Acceleration	ADB
Japan	-	-	*No diesel emission test*	Questionnaire
Japan	Opacity	-	Free Acceleration	BIVV
Malaysia	HSU	-	-	ADB
Nepal	HSU	-	-	ADB
New Zealand	Opacity	-	Free Acceleration	Questionnaire
Pakistan	HSU	-	Free Acceleration	ADB
Panama	HSU?	-	Free Acceleration	Questionnaire
Paraguay	Opacity	-	N/A	Questionnaire
Philippines	Opacity	-	Free acceleration	ADB
Republic of Croatia	Opacity	-	Free acceleration	Questionnaire
Singapore	HSU	Yes	Loaded lug-down	BIVV
Singapore	HSU	Yes	Lug-down	Questionnaire
Singapore	Opacity	-	Free acceleration	Sierra
South Korea	HSU	Yes	Lug-down mode	BIVV

Country	Exhaust components measured [1]	Chassis Dyno?	Test	Source[2]
Sri Lanka	HSU	-	Idle	ADB
Switzerland	Opacity	-	Free acceleration	Questionnaire
Thailand	HSU	-	Free acceleration	ADB
Thailand	HSU	-	Free acceleration	ADB
Thailand	N/A	-	Loaded	ADB
Thailand	HSU	-	Filter test, free	ADB
Thailand	N/A	-	Filter test – loaded	ADB
Turkey	Opacity	-	Free acceleration	Questionnaire
USA, Arizona	Opacity	Yes	Loaded cruise mode	Sierra
USA, California	Opacity	-	Free acceleration	Sierra
USA, Colorado	Opacity	Yes	Lug-down, free	Sierra
USA, Connecticut	Opacity	Yes	Lug-down	Sierra
USA, Idaho	Opacity	-	Free acceleration	Sierra
USA, Kentucky	Opacity	Yes	Lug-down, kerb idle	Sierra
USA, New Mexico	Opacity	-	Two-speed idle	Sierra
USA, Ohio	Opacity	Yes	ASM2525	Sierra
USA, Oregon, Medford	CO, Opacity	-	Two-speed idle, OBDII	Sierra
USA, Oregon, Portland	HC, CO, NO_x, Opacity	Yes	BAR31, kerb idle, OBDII	Sierra
USA, Rhode Island	Opacity	Yes	BAR31	Sierra
USA, Utah	Opacity	Yes	Loaded cruise mode, free acceleration	Sierra
USA, Vermont	Opacity	-	Free acceleration	Sierra
USA, Washington	Opacity	-	Free acceleration	Sierra
Vietnam	HSU	-	Idle	ADB

Table 11 – Summary of PTI emission tests and limit values for non-EU countries (N/A = not available).

(1) HSU = Hartridge Smoke Unit; m^{-1} = light absorption coefficient; RB = Filter or Bosch smoke meter unit

(2) ADB = (Asian Development Bank (ADB), 2001); BIVV = (Lemaire and Page, 2007) [BIVV= Belgisch Instituut voor Verkeersveiligheid (Belgian Institute for Road Safety)]; Questionnaire - see Appendix E; Sierra = (Sierra Research Inc., 2001).

4.2. Different aspects for a new test procedure

The outcome for a new PTI test procedure should involve 3 different aspects:

1. The vehicle test condition including the use of OBD information as well as a tailpipe emission test: a fixed schedule of vehicle operation which allows an emission test to be conducted under reproducible conditions and considering the different PTI regimes in Europe. This could be a specific unloaded condition or a loaded condition obtained by a driving cycle. These driving cycles can be divided into loaded steady-state and loaded transient cycles, depending on the character of speed and engine load changes.

   In annex 2, we have listed the vehicle test conditions which are currently used, or have been used in the past, in PTI tests as described in the Teddie study (CITA, 2011). This work drew upon earlier reviews (*e.g.* Samaras & Zachariadis, 1995; Brown, Bryett & Mowle, 1999; Norris, 2002).

2. NO_x measurement equipment as discussed in chapter 4.

3. Additional equipment, if necessary (measurement of oil temperature, rpm, OBD data, etc.)

Posada et al. (2015) introduced two newer measurement technologies that could be utilized to improve I/M programs for heavy duty vehicles:

(1) Measurement of particles with laser-light-scattering photometry (LLSP) and
(2) Measuring NO_x and NO_2 using NDUV.
Furthermore, alternative testing methods could complement or replace traditional I/M methods e.g.:
(1) On-Board Diagnostics (OBD)[4];
(2) Remote Sensing; and
(3) On-road Heavy-duty Emissions Monitoring System (OHMS).

Norris (2005) concluded that in the UK it was inappropriate to attempt to measure NO_x emissions using loaded proxy cycles to emulate emissions from the type approval loaded cycles for both LDVs and HDVs. In service NO_x testing should consist of a diagnostic check of key systems (or components) whose failure would lead to excessive NO_x emissions. This reduces the check to the correct functioning of the vehicles' NO_x abatement technology only. It is emphasised that this is a technology dependent diagnostic check.

The scope of the project should include the precise recommendations to measure NO_x emissions for the European Commission and Member States to amend the PTI Directive 2014/45/EU accordingly. These test procedures could be based upon the evaluation of a certain amount of NO_x air pollutants at a certain load or upon an evaluation of good working NO_x after-treatment systems. The study should

[4] This study likes to make a distinction between EOBD and OBD. EOBD is a European standard and only Emissions related. It should be in this context be read as EOBD.

evaluate all possible NO_x test procedures, including those not so evident in a European PTI centre e.g. chassis dyno tests and remote sensing, and all existing NO_x test equipment. Furthermore, the possibility to also detect the removal of particulate traps should be evaluated.

Two different kind of test procedures with a focus on NO_x emissions and applicable in a European PTI environment are identified:

- NO_x threshold test procedures.
- Component (after-treatment) test procedures.

Furthermore, complimentary measures could be combined with these PTI procedures, such as Remote Sensing or OHMS programs in order to identify high or low emitters. The detection of either dirty or clean vehicles can either bring forward or postpone the existing PTI regime.

4.3. Other consideration

4.3.1. NO_x behaviour during driving cycles

Favre, Bosteels & May (2013) tested among petrol vehicles also two (2) Euro 6 diesel vehicles on three different driving cycles: NEDC, CADC and WLTC. Vehicle "E" was fitted with a lean NO_x trap system and vehicle "F" with a SCR system. Some of their test results concerning NO_x emissions are highlighted below.

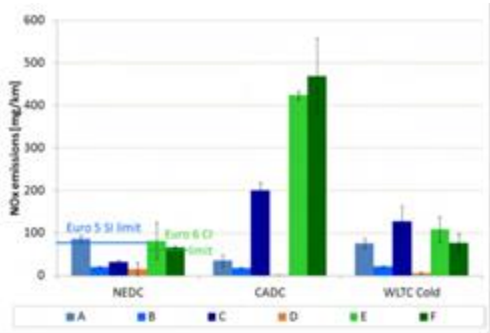


Figure 20 - NO_x emissions over the test cycles at 25°C. (Taken from Favre et al., 2013).
Note: The green bars, Vehicle "E" (LNT) and vehicle "F" (SCR), are the diesel vehicles.

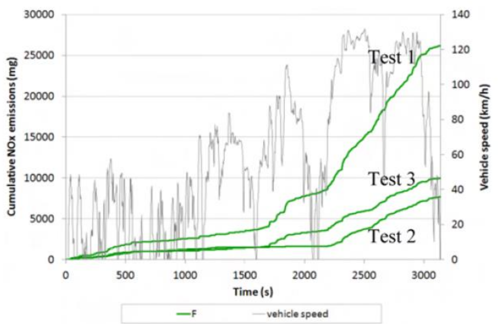


Figure 21 - Cumulative NO_x emissions of vehicle "F" (SCR) operated on CADC at 25°C. (Taken from Favre et al., 2013)

Figure 20 confirms the earlier findings that especially the Artemis CADC cycle has significant higher NO_x emissions than the type approval limits. On the other hand, the Artemis CADC cycle shows a large confidence interval, as illustrated by Figure 21. The large variations occur at the motorway part of the cycle, at the higher vehicle speeds.

The test temperature has an enormous influence on NO_x Emissions, especially for tests with diesel vehicles. The NO_x emissions increased when the vehicles are tested at -7°C instead of 25°C on both NEDC as WLTC test cycle (Figure 22).

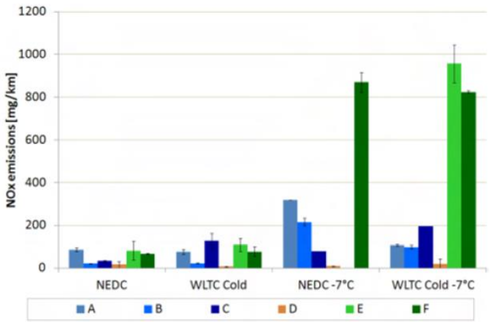


Figure 22 - NO_x emissions at 25°C and -7°C on NEDC and WLTC cycle. (Taken from Favre et al., 2013).
Note: The green bars, Vehicle "E" (LNT) and vehicle "F" (SCR), are the diesel vehicles.

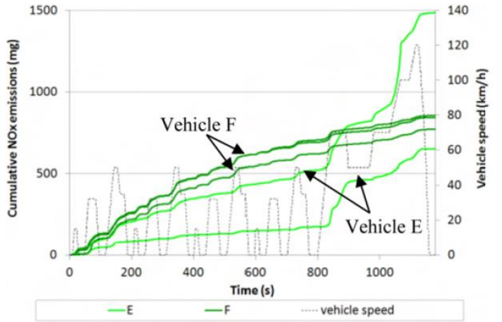


Figure 23 - Cumulative NO_x emissions of Diesel vehicles on NEDC at 25°C. (Taken from Favre et al., 2013).
Note: Vehicle "E" (LNT) and vehicle "F" (SCR).

The figures Figure 23, Figure 24 and Figure 25 illustrate the influence of the abatement system over the different driving cycles. The LNT system (vehicle "E"), in contrast to the SCR system (vehicle "F"), seems to control the NO_x emissions right from the beginning of the tests. At higher speeds the efficiency of the LNT systems tends to decrease. On the CADC cycle both systems almost have the same efficiency in the urban phase part. On the motorway phase, both systems LNT and SCR have breakthroughs of NO_x emissions.

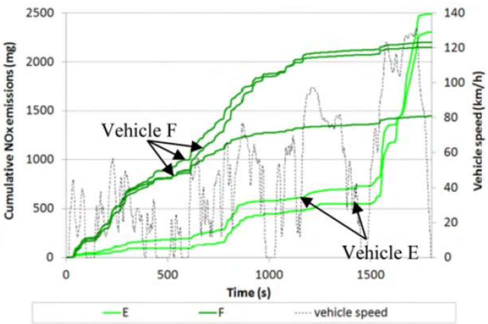


Figure 24 - Cumulative NO_x emissions of Diesel vehicles on cold-start WLTC at 25°C. (Taken from Favre et al., 2013).
Note: Vehicle "E" (LNT) and vehicle "F" (SCR).

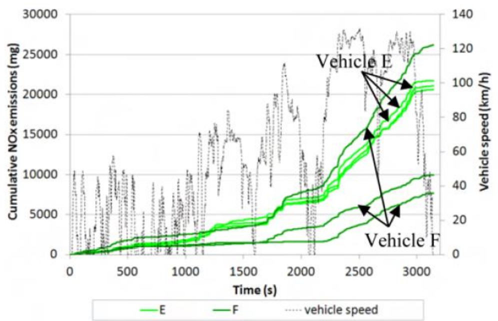


Figure 25 - Cumulative NO_x emissions of Diesel vehicles on CADC at 25°C. (Taken from Favre et al., 2013).
Note: Vehicle "E" (LNT) and vehicle "F" (SCR).

The abatement systems seem both to be more efficient with a cold-start than with a hot-start, as can be seen in Figure 26 and Figure 27. The authors of the study assign this to the specific calibration of the emission control systems or to temperature considerations.

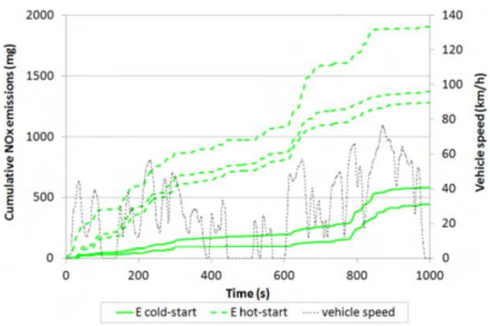


Figure 26 - Vehicle “E” (LNT) cumulative NO_x emissions on low- and medium-speed phases of WLTC at 25°C. (Taken from Favre et al., 2013).

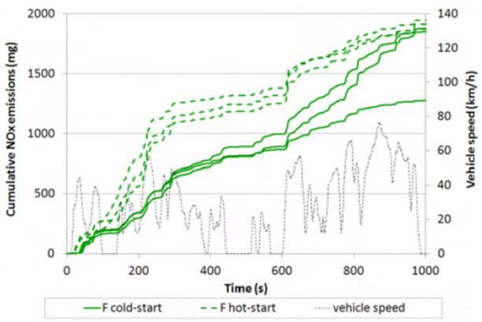


Figure 27 - Vehicle “F” (SCR) cumulative NO_x emissions on low- and medium-speed phases of WLTC at 25°C. (Taken from Favre et al., 2013).

In 2015 TNO Delft came to the same conclusions concerning cold and hot start on NEDC and WLTP cycles when they tested some Euro 5 Light Commercial vehicles (Kadijk, G., Ligterink, N. and Spreen, J., 2015a). The only difference is the engine temperature at the start of the test. Remark in Figure 28 that at the end of the NEDC cycle the tailpipe temperature of both tests are the same. The extremely higher NO_x emissions in the second part of the hot test cannot be explained by the test cycle, the engine or exhaust temperature. Similar findings were made on the WLTP test. The authors concluded that the vehicle shows different emission behaviour as well in the cold as in the hot test and that different emission control strategies are applied in both these tests.

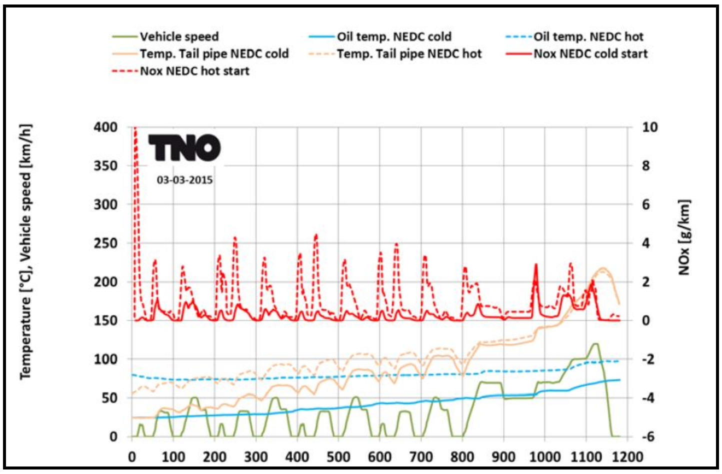


Figure 28 - Real time NO_x emissions on NEDC cycle with cold and hot start. (Taken from Kadijk et al., 2015a).

On the website of Cambustion (www.cambustion.com) some application notes can be found. Application note CLD03v01 shows that when during an acceleration the actual EGR delivery is lower than the desired one, a fast response NO_x analyser records a 2nd peak during the transient NO_x measurement. This is visualised in the Figure 29, taken from the application note CLD03v01.

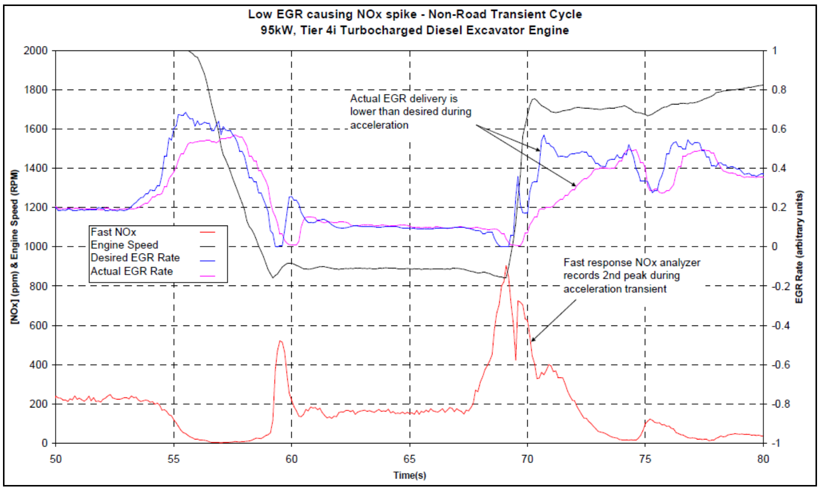


Figure 29 - Heavy Duty NO_x and EGR control. (Taken from Cambustion Application Note CLD03v01, n.d. b)

Furthermore, application note NDIR05v02 shows, that the EGR valve closes and opens again during a gear change with a significant NO_x production as a result. This can be seen in the figures Figure 30 and Figure 31.

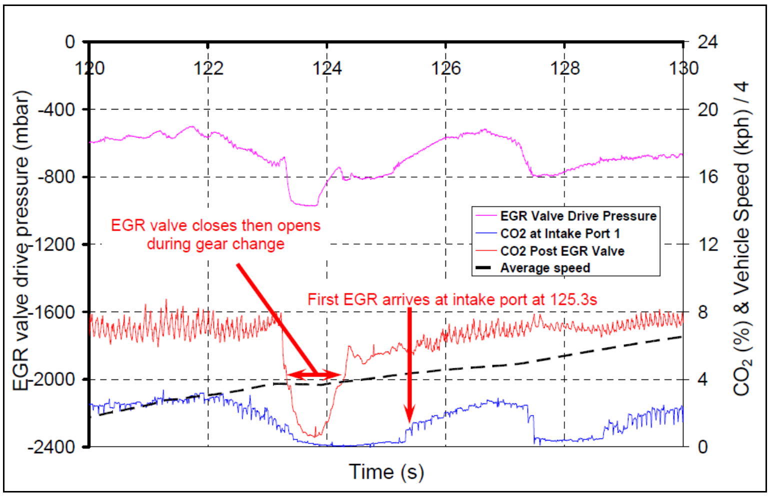


Figure 30 - Delay in EGR delivery during gear change. (Taken from Cambustion Application Note NDIR05v02, n.d. d)

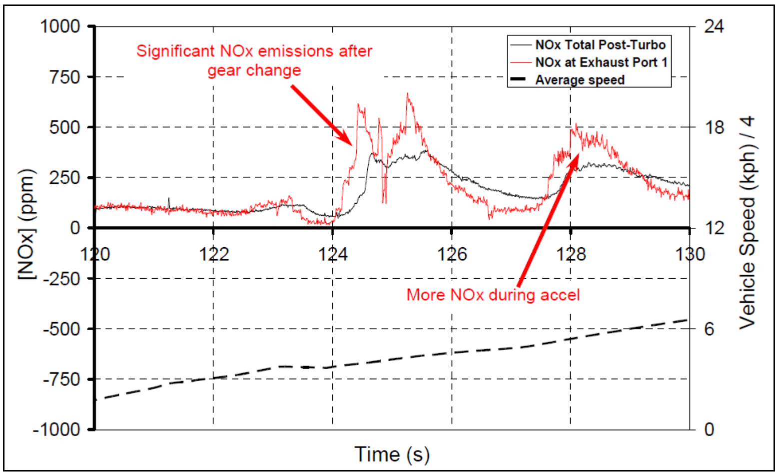


Figure 31 - NO_x emissions due to EGR delay. (Taken from Cambustion Application Note NDIR05v02, n.d. d)

4.3.2. NO_x PM trade-Off

Nitric oxide, NO, emissions are maximized at high temperatures when the air/fuel mixture is slightly lean of stoichiometric. They are limited during a lean combustion by low flame temperature (extremely lean) and during a rich combustion by a lack of excess O_2. In the latter, PM emissions will occur. In fact soot particles are formed in the locally rich regions of the inhomogeneous combustion. Hence, decreasing the combustion temperature (e.g. by exhaust gas recirculation) results in lower NO_x emissions but also in an increase of PM. This dilemma is known as the NO_x-PM trade-off.

Especially with engines before 2000, McCormick, Graboski, Alleman, & Alvarez (2003) detected higher NO_x emissions up to levels that are close to emission standards, as seen in Figure 32, after the reparation of a PM problem. Most repairs after a negative opacity test involved fuel injectors, fuel pumps, fuel pump calibration, throttle controls and injection timing. The deterioration of injectors, pumps etc... lowers combustion temperature with lower NO_x emissions as a result. Furthermore, Engine operating strategies that lower NO_x emissions, and thus lowering the engine temperature give an increase in PM.

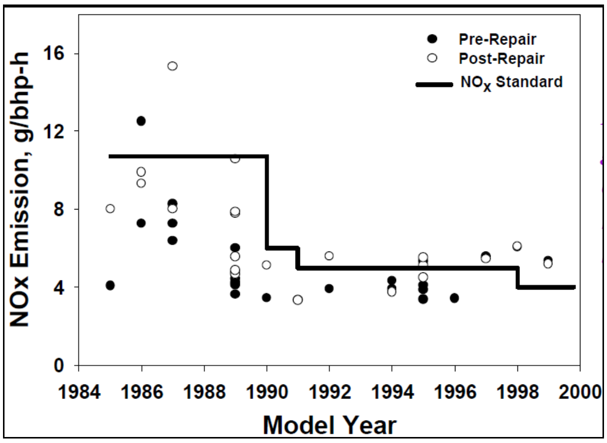


Figure 32 - NO_x emissions after repair of PM problems compared with the NO_x emissions standards. (Taken from McCormick et al., 2003).

4.3.3. Idea of Fast-Pass / Fast-Fail

In several countries, such as Belgium, the Netherlands, Finland and the UK (Driver & Vehicle Standards Agency, 2014), a fast pass/fast fail criteria for the opacity test is implemented in their emissions procedure. This is the option described in Directive 2010/48/EC to avoid unnecessary testing. Similar principles can also be taken into account to determine a test procedure.

4.3.4. An innovative dynamometer (Latham S., 2007)

Latham (2007) described an idea of an innovative dynamometer which consists of free-running rollers to provide a potential cheap representative roadside emission procedure. The system uses the vehicles brakes to apply speed and load to the engine. Of course the vehicle ABS and related systems have to be disengaged before performing the test. The method is a kind of "lug down" test which requires applying full throttle to drive the road wheels to a reasonable operating speed in gear and applying the vehicle brake to apply load to the engine. The brake would be gradually depressed along with the accelerator until an engine speed and a specific load is reached. The brakes need only to resist a fraction of engine load and be applied for short periods until the emissions stabilise so they can be measured. A cooling fan to cool the brakes when the vehicles are tested statically is to be installed.

Engine load information can be captured from the EOBD system.

Some disadvantages of the system are:

- Process would have to be repeated several times to obtain a stable estimate of emissions levels;
- Brake temperature can become high;
- Technique of applying a predetermined load and speed in a controlled manner using both the brake and accelerator are very difficult;
- Tests discussed in the paper were not very repeatable under these conditions;

It is clear that fully laden Heavy Goods Vehicles [HGVs] which have relatively powerful brakes will have the tendency to cause tyre damage due to the forces and speeds involved and thus the test is probably unsuited in this configuration.

4.3.5. Other assessment parameters: combustion efficiency by means of pollutant/CO_2 ratio, Emission Factor [EF] and Vehicle Specific Power [VSP]

Gas analysers register pollutant concentrations in units as parts per million by volume (ppm volume) and volumetric percent (Vol.%). Remote sensing devices express their results in parts per million metres (ppm.m) and percent meters (%.m). The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle. They are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. Therefore, ratios of CO, HC, or NO to CO_2, termed Q, Q' and Q'' respectively, are given by the remote sensing device. The ratios are constant for a given exhaust plume. The ratios reflect the deviation from perfect combustion encountered during the measurement. The combustion efficiency by means of pollutant/CO_2 ratio is based on the ratio of a specific gaseous pollutant (i.e. CO, HC and NO) to carbon dioxide (CO_2) in volumetric percent (vol.%). Here, the latter acts as an indicator for the combustion process efficiency. Ideally, the combustion of fuel results in power, CO_2 and water. Since only a small percentage of the carbon in the fuel is not emitted as CO_2, the concentration of the CO_2 can be directly correlated with the amount of fuel burned (Sira Ltd, 2003a; Sira Ltd, 2003b).

Assessing combustion efficiency by means of such ratios is interesting because under different engine operating conditions (i.e. lean, stoichiometric or rich burn) they will remain more or less the same, while the absolute emissions change. In addition, it is a more straightforward way of targeting engine malfunctions by indicating an inefficient conversion of the fuel (Sira Ltd, 2003a; Sira Ltd, 2003b).

From the pollutant/CO_2 ratios, the fuel composition and density calculated Bisshop (2014) the emission factors as given by Equation 13, Equation 14 and Equation 15:

$$Q = \frac{\%\ CO}{\%\ CO_2}$$

Equation 10: Q as the CO/CO2 ratio

$$Q' = \frac{\%\ HC}{\%\ CO_2}$$

Equation 11: Q' as the HC/CO2 ratio

$$Q'' = \frac{\%\ NO}{\%\ CO_2}$$

Equation 12: Q'' as the NO/CO2 ratio

$$EF\ CO\ \left[\frac{gCO}{kg}\ fuel\right] = \frac{28 * Q * 860}{(1 + Q + 6Q') * 12}$$

Equation 13: Emission Factor CO as given by Bisshop (2014)

$$EF\ HC\ \left[\frac{gHC}{kg}\ fuel\right] = \frac{2 * 44 * Q' * 860}{(1 + Q + 6Q') * 12}$$

Equation 14: Emission Factor HO as given by Bisshop (2014)

$$EF\ NO\ \left[\frac{gNO}{kg}\ fuel\right] = \frac{30 * Q'' * 860}{(1 + Q + 6Q') * 12}$$

Equation 15: Emission Factor NO as given by Bisshop (2014)

These EFs represent the instantaneous gaseous emission of a certain pollutant in grams per litre of fuel burned.

During the San Diego 9th CRC On-Road Vehicle Emissions Workshop the concept of Vehicle Specific Power [VSP] was introduced as a useful parameter for remote sensing and emission studies (Jimenez, McClintock, McRae, Nelson & Zahniser, 1999b). It is the ratio of instantaneous vehicle power to vehicle mass. The VSP is expressed in kilowatt per tonne (kW/tonne)

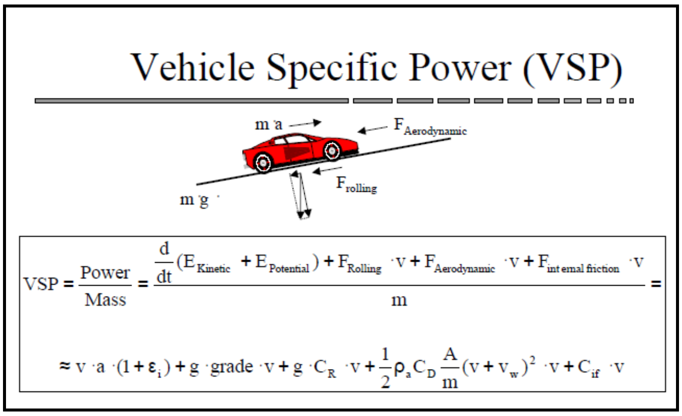


Figure 33 - VSP. (Taken from Jimenez et al., 1999b)

$$VSP\ [\frac{kW}{tonne}] = v \times (1{,}1 \times a + 9{,}81 \times slope[\%] + 0{,}132) + \frac{1}{2} \times \rho_{air} \times \frac{C_x \times A}{m} \times (v + v_w)^2 \times v$$

Equation 16: Calculation of the vehicle-specific power as specified by Jimenez (1999a)

With :

v: vehicle speed expressed in [m/s];

a: the acceleration in [m/s²];

ρ_{air}: the air density in [kg/m³];

C_w: the drag coefficient, (can be obtained from vehicle-specific information databases*);*

*A: t*he frontal surface in [m²], (can be obtained from vehicle-specific information databases*)*;

m: the vehicle mass;

v_w: the wind velocity, (is often neglected in dynamo-campaigns).

The factor of *0,132* represents the rolling resistance for a reference speed of 25 m/s.

4.4. NO_x – threshold test procedures

4.4.1. Overview existing NO_x – threshold test procedures

Some countries and certain US states use more sophisticated test methods which more closely replicate real-world driving conditions. These involve engine loading and require the vehicle to be placed on a power-absorbing dynamometer. These tests are more suitable than idle measurements for the characterisation of NO_x, which is largely produced at higher engine loads and temperatures (McCrae *et al*., 2005).

Barlow, Latham, McCrae & Boulter (2009) described more than 250 Loaded transient driving cycles, most of them used in a laboratory to measure exhaust emissions and not suitable for PTI.

The Teddy study (CITA, 2011) identified 3 places where during PTI a NO_x emission measurement on diesel vehicles was conducted (Australia, China (Beijing) and USA (Portland and Oregon)).

Country	Exhaust components measured	Chassis Dyno?	Driving cycle, test procedure
Australia	NO_x, PM, Opacity	Yes	DT80, DT60
China, Beijing	Opacity, HC, CO, NO_x	-	Free Acceleration
USA, Oregon, Portland	HC, CO, NO_x, Opacity	Yes	BAR31, kerb idle, OBDII

Table 12 - Summary of PTI emission tests, from the TEDDIE study, which does have a NO_x measurement test procedure

A more recent study, (Posada et al., 2015) found that only in Australia a NO_x test regime for diesel vehicles (heavy-duty) exists. The vehicle test condition is the loaded transient DT80 cycle.
In their overview (see Table 13) also BAR31 and IM240 are identified as test driving cycles for NO_x measurement and Acceleration Simulation Mode (ASM) can potentially be utilised to measure NO_x. These cycles are used to test gasoline vehicles.

Chernich (2003) and Texas A&M Transportation Institute (2013) performed the CARB Test Cycle “Power Curve”, as presented in Figure 34, on each truck brought to their lab in order to evaluate the effectiveness of a NO_x screening test (Chernich) or diverted from the highways to the chassis dynometer setup for a field screening (Texas A&M Transportation Institute). After warming up the truck, the driver puts the truck in direct gear and gives it full throttle. A load is slowly applied, using the dynamometer until the engine lugs down to past its peak power. Chernich specified that this cycle was chosen to permit NO_x emissions testing, under high engine load conditions.

Test Name	Loaded or Unloaded	HDV or LDV	Test requirements	Pollutant measured	Comments
Idle test and two-speed test	Unloaded	LDV	Roadside	CO and/or HC	Poor correlation with chassis test emission results.
Acceleration Simulation Mode (ASM)	Loaded	LDV	LDV chassis testing	HC, CO, and potentially NO_x	Improvement over unloaded test; strong correlation with certification testing results. Applies to vehicles with three-way catalytic converters but not OBD.
IM240	Loaded	LDV	LDV chassis	HC, CO, and NO_x	NO_x, CO, and HC emissions results correlate better with certification chassis testing than with the ASM. Requires a centralized program to amortize the costs.
MA31/BAR31	Loaded	LDV	LDV chassis	HC, CO, and NO_x	Shorter chassis-based test but has been deemed just as capable of high-emitter identification.
FAS or SAE J1667	Unloaded	HDV	Roadside	Smoke opacity	Designed for mechanically operated diesel vehicles. It is inadequate for PM screening or for measuring NO_x.
Lug-down	Loaded	LDDV and HDV	Chassis test	Smoke opacity	Targets older, smoky vehicles. Not designed for measuring PM or NO_x.
DT80	Loaded	HDV	Chassis test	PM, NO_x	The most comprehensive protocol among all HDV loaded I/M testing.

Table 13 - Summary of testing protocols for I/M programs. (Taken from Possada et al., 2015).
Note: HDV: heavy-duty vehicules, LDV: light-duty vehicules, and LDDV: light-duty diesel vehicles

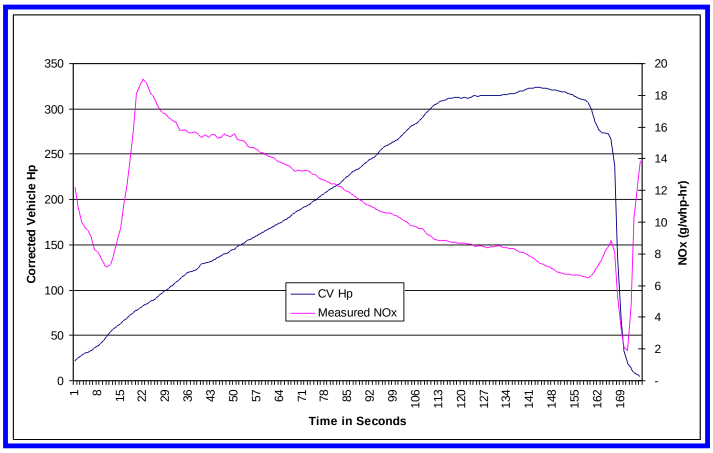


Figure 34 - the CARB Test Cycle "Power Curve". (Taken from Chernich, 2003)

As far as our study could establish, there are only a few locations (*e.g.* Australia and the US states of Oregon and Rhode Island) where a transient emission test is performed on diesel engines. In the Australian DT80 test an opacity measurement is still conducted for the continuation of the historical time series, together with the measurement of PM. It appears that Beijing is the only location at which a free acceleration test is used to measure NO_x.

Korea introduced in 2011 the KD147 mode for diesel vehicles (Park, 2015). KD147 mode (Figure 35) was benchmarked from Canada. At the moment only smoke density is measured with for Heavy Duty diesel vehicle the Lug-down 3 mode and for passenger's cars and light duty diesel vehicles the KD147 mode. The KD147 mode reflects more real driving and is more convenient to use than the lug-down 3 mode. Korea has ongoing projects to develop standards and methods for diesel NO_x measurement.

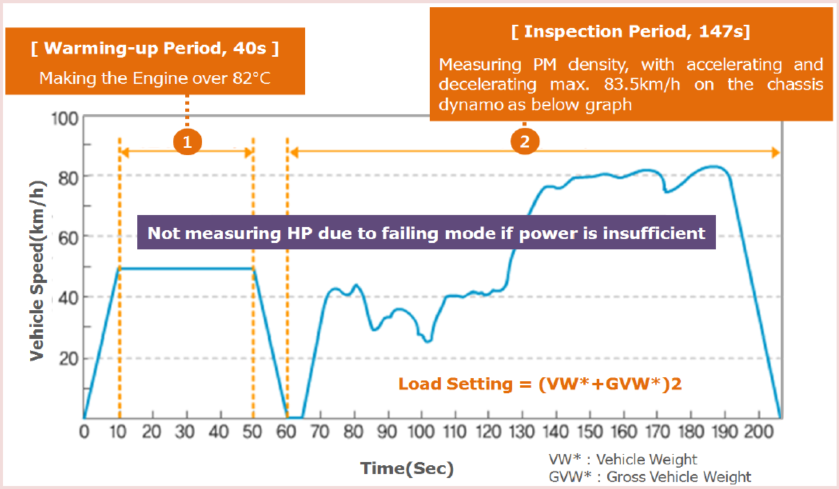


Figure 35 - KD-147 Mode. (Taken from Park, 2015)

Note : Canadian D147 - this test applies to diesel vehicles only. The driving test is a transient type of test that includes accelerations and decelerations as well as cruise conditions. The vehicle speed must closely follow a trace that is derived from the EPA75 federal test procedure. The test will last from 97 seconds to 147 seconds for all vehicles tested using the D147. The D147 cycle was in some Canadian areas used during AirCare, a vehicle emission test program, operational from 1992 to December 31, 2014.

4.4.2. Evaluation of the NO_x – threshold test procedures

Fung & Suen (2013) concluded that, since nitrogen oxides emissions are at idling negligible, unloaded tests are incapable of measuring these emissions. This type of test can include idling at both low and high engine speeds, or revving the engine several times. Such simple, low-cost procedures can serve as screening routines for high-emitting vehicles of some pollutants. However, the tests are sometimes inconsistent, are prone to manipulation, and suffer from high false failure rates (CITA, 2011).

The lug-down test, though better than the unloaded tests, is not designed for measuring diesel vehicle particulate matter (PM) and NO_x emissions (Fung & Suen, 2013; Posada et al., 2015).

In steady-state loaded tests the engine speed/load is held constant. Relatively inexperienced test facility employees are capable of conducting steady-state loaded tests, achieving acceptable accuracy at moderate cost. Transient loaded tests, in which the vehicle is operated through simulated driving cycles and loads, are longer, costlier, and require relatively skilled staff. They result in a complicated I/M system which lends itself to centralisation (United States Agency for International Development [USAID], 2004).

Many studies have shown that the correlation between exhaust smoke and NO_x emissions from diesel vehicles are poor, even when measured under a controlled load on a dynamometer. It has also found that diesel vehicles that had been repaired to reduce visual smoke may have increased NO_x emissions.

Anyon, Brown, Pattison, Beville-Anderson, Walls & Mowle (2000) compared emissions over various short tests and emissions over the CUEDC[5]. The correlation coefficients for the comparisons are given in Table 14.

The snap idle test proved to be an extremely poor indicator of PM levels, even though it provided a reasonable correlation with maximum CUEDC opacity levels. Its HC and NO_x results had the lowest correlation with the CUEDC of all the tests. The D550 and the lug-down tests also proved to be poor indicators of PM emissions. Their NO_x and HC results provided a fair correlation with the CUEDC. These tests were, nevertheless, very useful in highlighting a fundamental requirement for any in-service diesel test: the need to measure PM emissions under transient engine loading conditions. The two transient tests - the AC5080 and the DT80 - were the best-performing tests (Anyon *et al.*, 2000).

Short test	Correlation coefficient (R^2)					
	Average NO_x (g/s)	Average HC (g/s)	Average PM (LLSP) (mg/s)	PM filter (mg)	Average opacity (%)	Maximum opacity (%)
AC5080	0.95	0.92	0.70	0.71	0.87	0.80
DT80	0.90	0.85	0.63	0.58	0.68	0.81
Lug-down	0.60	0.68	0.22	-	0.26	0.68
D550	0.64	0.53	-0.18	-0.23	0.03	-0.23
Snap idle	0.47	0.23	-0.02	-	0.29	-0.59

Table 14 - Correlation between short tests and CUEDC. (Taken from Anyon et al., 2000).

The results of the above Table 14 after normalising for mass are given in the Table 15. The normalisation by mass is done by dividing the emission test results (g/km) by the vehicle test mass (tonnes) in order to link the emission levels to the useful payload and power output of the vehicle tested.

[5] CUEDC = Composite Urban Emission Drive Cycle, developed by the New South Wales Environmental Protection Agency in Australia. It consists of four segments, each of which represents driving in a different urban traffic condition (congested, minor roads, arterial roads and highway/freeway).

Short test	Correlation coefficient (R^2) – Mass Normalised			
	Average NO_x (g/s)	Average HC (g/s)	Average PM (LLSP) (mg/s)	PM filter (mg)
DT80	0.84	0.76	0.84	0.86
AC5080	0.68	0.68	0.88	0.84
Lug-down	0.33	0.54	0.61	-
Snap idle	0.23	0.46	0.39	-
D550	0.24	0.26	0.23	0.49

Table 15- Correlation between short tests and CUEDC – Mass Normalised. (Taken from Anyon et al., 2000).

After normalising for vehicle mass, Table 15, the DT80 performed better than the AC5080, with correlation R^2=0.84 for NO_x. Furthermore, Anyon et al. (2000) investigated the possibility to detect high polluters for PM, NO_x and smoke with DT80 and AC5080 tests. Both tests performed extremely well, except for the AC5080 in respect of NO_x emissions.

Via one of the authors of the ESMAP study, we received the following graphs (Figure 36, Figure 37, Figure 38 and Figure 39). Remark that these correlations for different cycles are given for an opacity test.

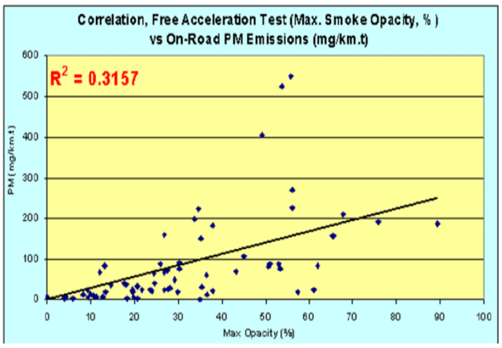


Figure 36 - Correlation for free acceleration test.

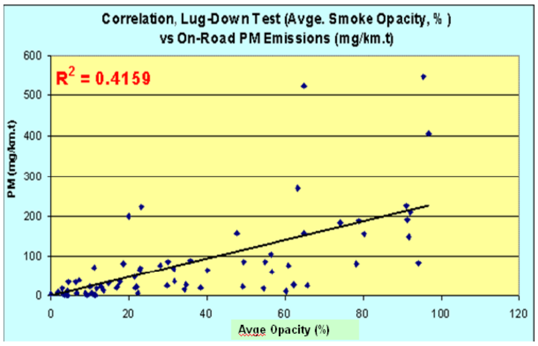


Figure 37 - Correlation for lug-down test

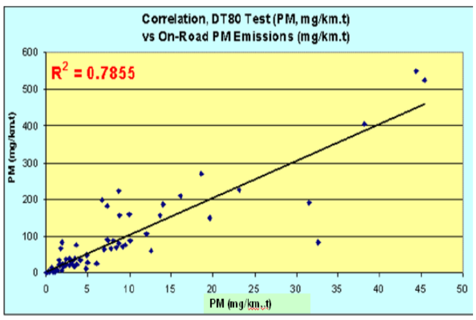


Figure 38 - correlation for DT80 test.

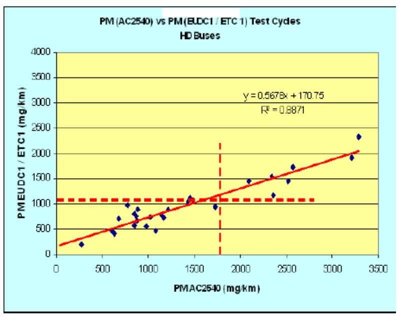


Figure 39 - Correlation for AC2540 test.

Anyon *et al.* (2000) also provided an overall test ranking based on quantitative and qualitative criteria. The results are shown in Table 16. The AC5080 and DT80 tests both rated highly, and were followed by the snap idle test. Because of the DT80's superior performance in identifying high emitters it was considered to be the best test.

Criterion		AC5080	DT80	Lug-down	D550	Snap idle
Correlation with CUEDC	NO_x	7	9	6	6	5
	PM	7	8	2	0	0
	Opacity	8	8	2	0	2
	HC	9	8	6	2	5
Sensitivity to reflect changes in emissions over the CUEDC		8	8	4	2	3
Ability to identify reasons for high emissions		6	6	4	2	2
Safety of application		8	8	8	8	9
Suitability for use across the range of vehicles tested		8	9	7	8	9
Ease of use		7	7	4	8	9
Time requirements		5	5	5	5	8
Resource requirements		5	5	7	7	10
Suitability for use in large-scale in-service vehicle testing programme		8	7	7	2	9
Overall rating		**86**	**88**	**62**	**46**	**64**

Table 16 - Evaluation of short tests (10= highest potential value, 1= no value). (Taken from Anyon et al., 2000).

4.5. NO_x – abatement component test procedures

4.5.1. Exhaust gas recirculation (EGR) component tests – "Capelec"

During the 8th CITA WG2 meeting, 7th - 8th October 2015 in London the French Capelec company introduced a possible idea to test the functionality of the EGR valve (Petelet, 2015).

The proposed procedure is based on two stages where the status of the EGR valve is known:

- Fast Idle (EGR should be open)
- Maintained High rpm level (EGR will close)

Furthermore, the action of the EGR has a direct impact on the engine filling ratio.
Capelec calculate the engine filling ratio $\rho_{remplissage}$ as follows (G. Petelet, personal communication, March 20, 2016):

$$\rho_{remplissage} = \frac{\text{Real Mass Flow}}{\text{Mass Flow par construction}}$$

$$\text{Mass Flow par Construction} = \frac{60 * N}{2} \cdot \frac{Cyl}{1E6} \cdot \rho_{air}$$

$$\rho_{remplissage} = \frac{\dot{m}_{air}}{\frac{60 * N}{2} \cdot \frac{Cyl}{1E6} \cdot \rho_{air}}$$

Equation 17: Capelecs engine filling ratio $\rho_{remplissage}$

With :

$\dot{m}_{air}$: Air Mass flow in [kg/h], taken from MAF sensor via OBD;
N: revolutions per minute in [rpm], taken via OBD;
Cyl: Engine displacement in [cm^3];
ρ_{air}: the air density in [kg/m^3];

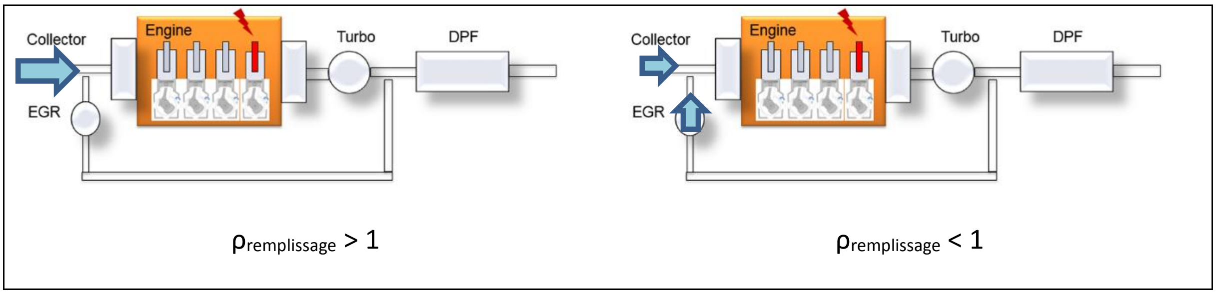


Figure 40 - Capelecs engine filling ratio $\rho_{remplissage} > 1$ and $\rho_{remplissage} < 1$. (reproduced by kind permission of Capelec).

Figure 40 shows the meaning of the engine filling ratio $\rho_{remplissage}$. When the ration $\rho_{remplissage} > 1$ means a normal operation due to the turbo and that $\dot{m}_{air} > \frac{60 * N}{2} . \frac{Cyl}{1E6} .\rho_{air}$, and thus EGR valve is closed. When the EGR valve is open, a part of the intake air comes from the EGR and thus $\rho_{remplissage} < 1$.

Capelec propose the following test conditions:

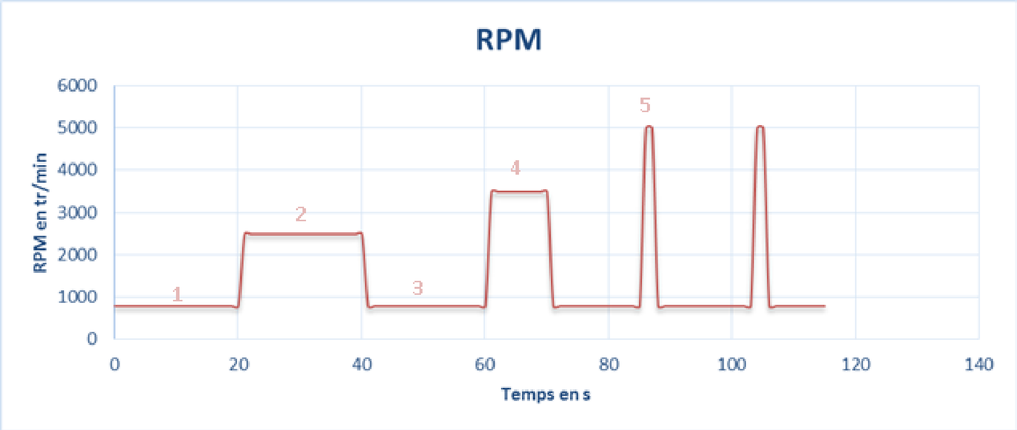


Figure 41 - "Capelec" cycle to test EGR. (reproduced by kind permission of Capelec).

1: 20s at Idle rpm : acquisition of NO_{x1}, rpm and Engine filling ratio ρ_1
2: 20s at Fast Idle rpm (2500 rpm): acquisition of NO_{x2}, rpm and Engine filling ratio ρ_2
3: 20s at Idle rpm: acquisition NO_{x3}, rpm and Engine filling ratio ρ_3
4: 10s at high rpm level (> 3500 rpm): acquisition NO_{x4}, rpm and Engine filling ratio ρ_4
5: 2 free acceleration: maximum pic NO_{x51} and NO_{x52}, rpm, Engine filling ratio pic ρ_{51} and ρ_{52}

During each procedure's state rpm is monitored via OBD. The user will be informed with colour code regarding live rpm value validating (or not) the rpm for this procedure's state. A valid rpm is required in order to validate each state and each state transition. In state 4 minimum 5s at 3500 rpm is needed. In case of rpm limited vehicles the procedure will nevertheless go further on to the next stages (possible in stages 4 and 5), with a remark if the rpm was not validated.

Evaluations based on the engine filling ratio as well as on the NO_x values are taken into consideration:

- Engine filling ratio criteria :
  (1) $p_2 < 1$ (EGR open during Fast Idle)
  (2) $p_4 > 1$ (EGR closed at high rpm)
  (3) $p_{51} > 1$ and $p_{52} > 1$ (EGR closed during free accelerations)
- NO_x criteria
  (4) $NO_{x4} / NO_{x2} > 1.2$ (higher NO_x values when EGR valve closed)
  (5) NO_x $NO_{x3} / NO_{x1} > 1.5$ or $NO_{x1} < 50$ ppm and $NO_{x3} < 50$ ppm
  (If those 2 NO_x values are different at idle rpm = this means that there is an EGR action on one of them).

Note that in case of rpm limited vehicle at 2500 rpm, the engine filling ratio criteria could not be used due to the fact that measures at stage 4 and 5 are impossible to proceed.

4.5.2. Exhaust gas recirculation (EGR) component tests – "Norris (2005)"

Norris described in the study "Low Emission Diesel Research" (2005) a test procedure to check the continued operation of the EGR unit by the use of 4-gas analysers. The investigation into the potential use of thermometry to detect malfunctioning EGR valves was not found to be appropriate to develop a practical in-service test since accessibility (e.g. engine covers) and thus dismantling was required.

He introduced a gentle acceleration. The study showed that during gentle accelerations EGR systems operate in different ways. To ensure that the test included a working region of the EGR the engine speed was slowly increased from idle to a suitable upper limit (3,500 rpm), with the vehicle unloaded (*i.e.* neutral gear selected). The rate of increase in the engine speed was not described, but a slope of 50 rpm per second would appear to be reasonable. We refer to this test hereafter as 'Norris-A'. Since the EGR unit is an important emission-reduction system for NO_x emissions, this could be an important test. In the study itself the working of the EGR was determined using concentrations of CO_2 and O_2.

On all 8 tested vehicles a difference at a certain rpm (in the examples of Figure 42 and Figure 43 it as at 2,500 rpm) in exhaust gas composition (CO_2 and O_2) was seen as the EGR switches from gas recirculation to preventing exhaust gas from recirculating.

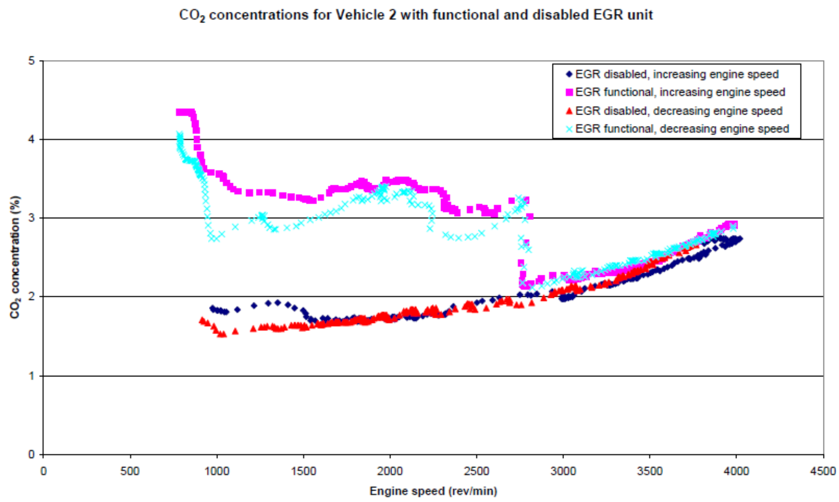


Figure 42 - Illustrative example of CO_2 tailpipe concentrations as a function of engine speed from a vehicle fitted with an EGR system. (Taken from Norris, 2005)

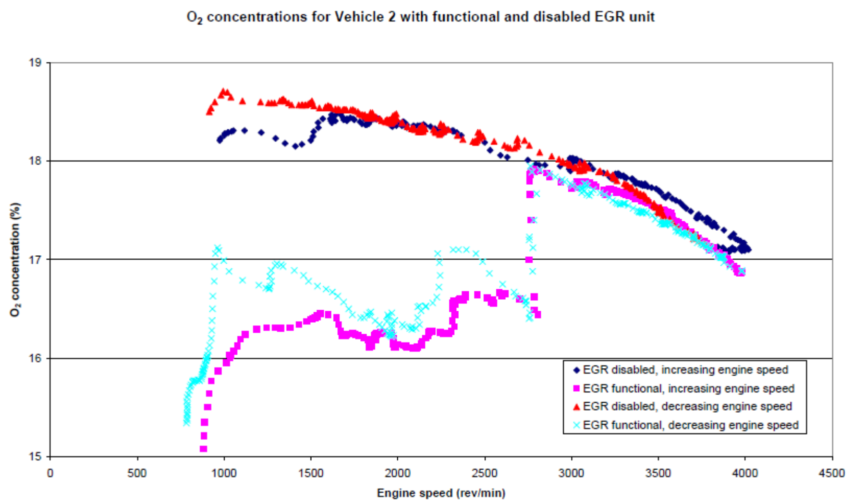


Figure 43 - Illustrative example of O_2 tailpipe concentrations as a function of engine speed from a vehicle fitted with an EGR system. (Taken from Norris, 2005)

However, the narrow engine speed range where over the EGR unit is turned off, as seen in the Figure 42 and Figure 43, was noticed in 3 of the 8 tested vehicles. For the remaining 5 vehicles the turning off is pulsed over a wider range. This arises because of differences in the way EGR units operate.
Norris introduced therefore, a proposal for a two engine speed test. However, the low and high optimum engine speeds (when the EGR is on and off, respectively) varies from vehicle to vehicle. From the CO_2 and O_2 concentrations at these optimum speeds it could be concluded that there are no universally applicable concentration thresholds. No O_2 (or NO_2) concentration is appropriate for all vehicles since for some vehicles concentration at the lower speed could be in the range of the concentration at the higher speed for other vehicles.
Notwithstanding, for each vehicle the CO_2 concentration at the optimum lower engine speed is higher than the concentration at the optimum higher engine speed. For the EGR valve that is stuck (being either permanently on or off) the order is the other way around. For the O_2 concentrations the order is reversed.

A stuck EGR valve can be deducted at the lower engine speed from the Table 17.

EGR Function	CO_2 concentration	O_2 concentration
Open, EGR occurring	3 % - 5 %	14 % - 16.7 %
Closed no EGR occurring	1.8 % - 2.5 %	17.2 % - 18.5 %

Table 17 - EGR function at low engine speed. (Created from Norris, 2005)

Norris stated that the measurement precision is relatively high for the following reasons:

- 2 independent sensors: CO_2 and O_2;
- Consistency between the 2 sensors can be checked since these gas concentrations are related : 1.5 CO_2 + O_2 = 21 to 21.5;
- Other meter checks can be made e.g. use of calibration gases;

- CO_2 and O_2 are the primary products of combustion. Consequently, they are a fundamental consequence of the engine running and are not subject to perturbations like catalyst temperature.

In the same study another test cycle was used in order to turn on the EGR. For some of the vehicles tested merely by gently touching the accelerator pedal at idle (up to 900-1000 rpm) caused the EGR unit to turn on, and then after a certain time (up to 2 minutes) to turn off again. We refer to this test hereafter as ‘Norris-B’. This procedure was not applicable to all vehicles, but for those where it worked it was adjudged that this test was inherently simpler, quicker and has better signal to noise characteristics than for measurements at engine speed above idle.

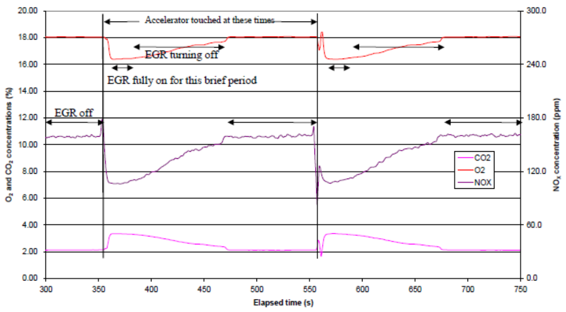


Figure 44 - Vehicle "1" – Norris-B cycle: emissions at idle when EGR functional. (Taken from Norris, 2005)

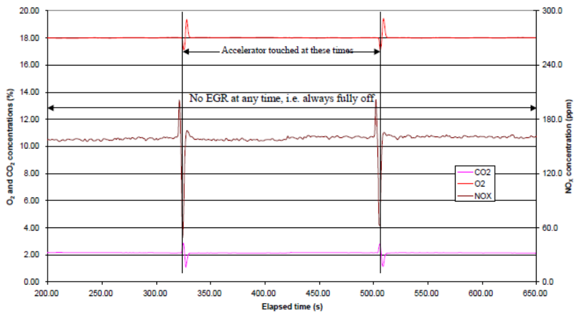


Figure 45 - Vehicle "1" – Norris-B cycle: emissions at idle when EGR disabled. (Taken from Norris, 2005)

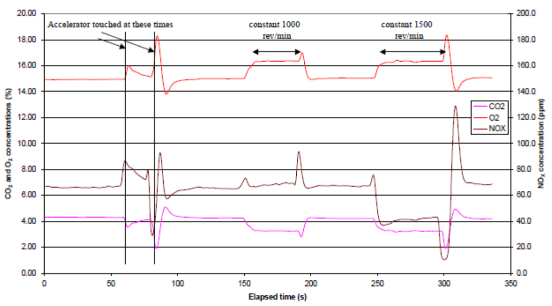


Figure 46 - Vehicle "2" – Norris-B cycle: emissions at idle when EGR functional. (Taken from Norris, 2005)

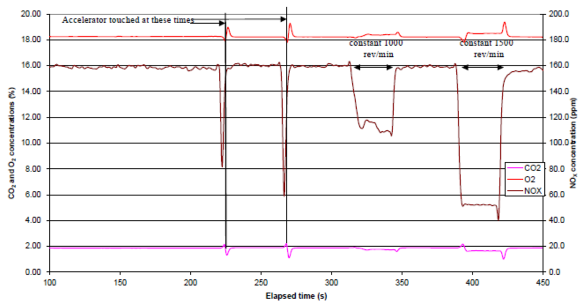


Figure 47 - Vehicle "2" – Norris-B cycle: emissions at idle when EGR disabled. (Taken from Norris, 2005)

4.5.3. Diagnostic screening test – "Pillot et al. (2014)" – "Spheretech-Bosch"

As already mentioned in 2.4., the French study (Pillot et al., 2014) monitored the different gas fractions during an engine cycle composed of 4 successive steady-state regimes without any load and an engine stop delay. The engine cycle was the following:

- 40 seconds at idle
- 40 seconds at 3200 rpm
- 15 seconds at full throttle
- 30 seconds at idle
- 90 seconds from the engine shut-off

The Non-dispersive infrared analyser [NDIR] was equipped with a software program which displays and analyses the exhaust gas composition and can detect defects in the combustion line and after treatment system. More than 130 defects and combinations of defects can be identified based on a comparison to threshold values. Here for a necessary input data e.g. brand and model of the vehicle, vehicle mileage, model year, engine technology, fuel injection type and MIL, etc. is needed.

Via personal communication between a member of the Project Steering Group and Mr. Pillot we were informed that the equipment used in the study was a Spheretech-Bosh equipment. Petelet (2015) explained in the 8th CITA WG2 the principle of Spheretech-Bosch: The O_2 and CO_2 concentrations give an image of the richness of an air/fuel mixture, which allows evaluating indirectly the clogging of the air intake. Hence, when air intake is clogging, less air is passing through so as a result shows an increase of the ratio between the fuel injected flow rate and the air intake flow. The first flow has to be constant in order to maintain the load, and the latter, the air intake flow is decreasing. The O_2 and CO_2 concentrations at tail pipe vary inversely proportionally when the richness of an air/fuel mixture is increasing more or less as a monotonic and linear function. Furthermore, maximum engine contamination is matching with particular gas concentration. It seems that Spheretech has two key thresholds available (Niv1: dirty and Niv2: very dirty).

4.5.4. AVL DiTest rpm ramp for NO_x measurement – "Schweiger (2016)"

In a special presentation for this SET II project, Schweiger informed us about the AVL research to a suitable unloaded idle condition for NO_x measurement. They investigated 12 different acceleration ramps with different rotational speeds (rpm) and ramp times. The focus went, due to the fact that most different modern Diesels engines don't reach 3500 rpm during idle, to idle ramps less than 3500 rpm. Different defects were simulated via application software (ETAS-INCA). INCA is a measuring and calibration environment for electronic control units. The following defects: LNT/CSF full, EGR 20%, EGR 30%, EGR 50%, EGR off (0%) and cooler bypass off, were introduced on 2 vehicles (a 4-Cylinder EU6-RDE Diesel passenger car (2l capacity, 110kW) with NOx-storage catalyst, DPF and inactive SCR-system and a 6-Cylinder EU6-RDE Diesel passenger car (3l capacity, 190kW) with NOx-storage catalyst, DPF and active SCR-system).

After evaluation, they propose the following test procedure:

- Coolant temperature: >80°C
- The engine has to be accelerated within the defined scatter band (red lines of Figure 48). The acceleration from idle speed to approx. 2500rpm should be done constantly within 4 – 11 seconds.
- Keeping the rpm stable at 2500rpm for about 5-6 seconds
- Immediate release of the gas paddle after this 5-6 seconds

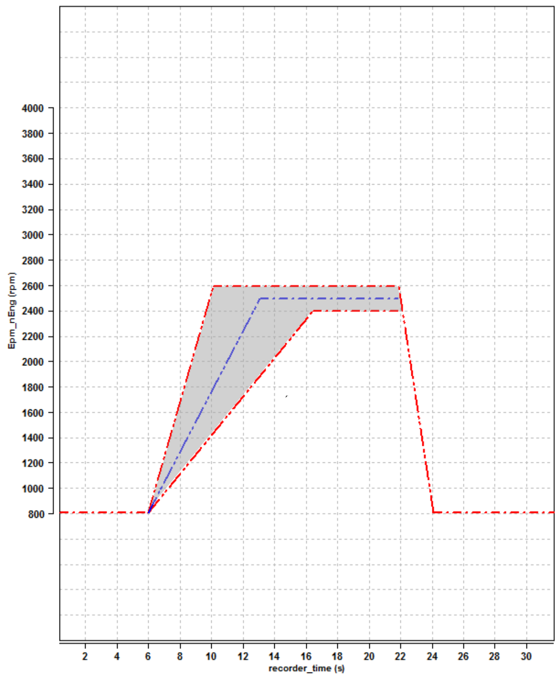


Figure 48 - AVL unloaded idle cycle for NO_x measurement. (Taken from Schweiger, 2016).

The max NO_x value, during this idle acceleration is measured.
The results with the proposed ramp are shown in Table 18.

Failure	NOx measured (ppm)
Vehicle in good condition	< 20 ppm
LNT/CSF Full loaded, functionality locked (rich operation)	230 ppm
EGR locked at 20%	100 ppm
EGR locked at 30%	140 ppm
EGR locked at 50 %	260 ppm
EGR locked at 0 %	110 ppm

Table 18 - AVL Ramp test results. (Created from Schweiger, 2016)

4.6. Remote Sensing (RSD) and On-road Heavy-duty Emissions Monitoring System (OHMS)

In the US, remote sensing has already been in use for two decades (Bishop & Stedman, 2008). In fact, Donald H. Stedman (University of Denver) invented an on-road remote sensor for vehicle emissions (Fuel Efficiency Automobile Test; FEAT) as well as an on-road heavy-duty truck measurement system (On-road Heavy Duty Monitoring System; OHMS). Opus Inspection licensed and commercialized the FEAT system under its Accuscan™ brand. Opus has used its remote sensors to complement United States periodic technical inspection (PTI) programs since the mid-1990s and currently collect over 10 million measurements annually for both Monitoring and Screening applications.

In order to save time and money, EPA introduced remote sensing within the concept of “clean screening” as part of the Inspection/Maintenance programs. A vehicle can be exempt from the next scheduled PTI test when it has been identified as a vehicle producing low emissions. (note: In the US PTI is often limited to an emission check).
This clean screening could be:

- Using conventional remote sensing devices (RSDs);
- Vehicle emissions low emitter profiling (based on the statistics of the historic failure rate) and/or;
- Implementing model year (vehicle age) exemptions (EPA, 1998).

Opus Inspection presented its Accuscan™ technology during the CITA conference in Dubai (Sands, 2015). They also made a live demo of their unmanned system on the road. The remote sensing device is described well by Borken-Kleefeld (2013) and the Amt für Abfall, Wasser, Energie und Luft (AWEL) of the Kanton Zürch in Switzerland (http://www.awel.zh.ch/internet/baudirektion/awel/de/aktuell/mitteilung/2016/lh_rsd_bericht.html). Vehicle remote sensing is a non-intrusive technique based on the spectroscopy (light absorption) principle able to screen the emissions of several hundreds vehicles in one hour. Remote sensing measures massively and unobtrusively the real driving emissions of a circulating fleet while considering its specific kinetic conditions. An exhaust plume is screened by an Infra-Red and Ultraviolet light source. Via the attenuation of the IR light at specific wavelengths the concentrations of the emissions CO2, CO, and HC are determined. The same principle is used for the NOx and PM (opacity) concentrations via UV light. Modern remote sensing devices can also measure NO2, NH3 and SO2 (Borken-Kleefeld, 2013). Furthermore, Borken-Kleefeld specified the measurement of NOx and opacity. The simultaneous measurement of NO and NO2 is desirable in order to have an accurate total result of NOx emissions from diesel vehicles with modern after-treatment devices. If the opacity is measured using both IR and UV wavelengths, black smoke can be differentiated from blue or white smoke. The concentrations are given for a specific vehicle at the specific driving condition (speed and acceleration) when it passes the remote sensor.

The system consists of the following elements:

- Light source (IR/UV) and detector module;
- Lateral transfer Mirror;
- Speed and Acceleration detector;
- Smart Camera (License plate recognition);
- Data recording device;
- Data Processing & Video Display.

(Sands 2015; Niranjan Vescio from Opus Inspection, personal communication, January 29, 2016).

Remote sensing devices measure emissions in parts-per-million-metres (ppm.m) and percent-meters (%.m). The exhaust plume path length and density of the observed plume are variable depending upon the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle, etc... Since only a small percentage of the carbon in the fuel is not emitted as CO2, the increment in the instantaneous concentration of the CO2 is directly proportional to the amount of fuel consumed. Therefore, ratios of CO, HC or NO to CO2, are given by the remote sensing device from which emission factors in gram pollutant per kg fuel are calculated. Bishop (2014) describes the calculation of emission factors from the pollutant/CO2 ratios, the fuel composition and density.
Remote sensing devices have their strengths and limitations as mentioned in Table 19.

Strengths	Limitations
Large sample size: RSDs can provide several hundred valid measurements per hour	Suitable traffic conditions and measurement set-up (clearly separable single lane traffic, steady acceleration, engine under load).
RSDs operate under real driving conditions	RSDs do not operate during rain, snow, high winds or other adverse weather conditions to ensure accurate, uncontaminated readings.
RSDs can provide very accurate emission results on fleet averages due to the large sample size.	RSDs excludes emissions from idling or during deceleration (insufficient exhaust to measure).
RSDs can offer coarse statements about an individual vehicle's emission rate adequate for screening purposes when on-road measurements are suitably qualified.	RSD emissions are measured at moderate VSP and are not representative under highway driving conditions.
The following applications are brought forward as particularly suitable for vehicle RSD techniques: • Fleet emission monitoring (Fleet characterisation) • Emission Program evaluation • Cross-check on I/M performance • High emitter screening • Clean screening (Low emitter screening)	RSDs are set-up to measure hot exhaust emissions, thus cold engines are to be excluded.
	Vehicle information obtained via smart camera's (license plate recognition) are limited to the vehicles data registered in the specific database (limited to the vehicles registered in a certain state or jurisdiction)

Table 19 - RSD's Strengths and Limitations. (Created from e.g. Borken-Kleefeld, 2013 and website Opus inspection)

In Europe, use of Remote Sensing is limited to some countries or regions and to some university research institutes such as (in alphabetic order):

- Switzerland: EMPA Swiss Federal Laboratories for Materials, Science and Technology had in their research on behalf of the Federal Office for the Environment FOEN (CH) "Validation measurements Remote Sensing - PEMS - Chassis Dyno" the aim to validate the accuracy of the driving situation, the accuracy of the emission measurement and the influences on the measurement principle. Götsch & Alt (2015) gave also an overview of the NO and CO emission measurements on a yearly one month remote sensing campaign from 2000 until 2015. The average CO concentration for cars have been reduced since 2000 by 50 %, although they have been stagnating since 2007. For NO, a reduction of 30 % is observed. Since 2013, the downwards trend is broken. Diesel cars have much higher NO_x values than the threshold value for every model year from 1995 until 2015. On the other hand, Petrol cars seem to have met the threshold values for the last 10 years.
- Austria: IIASA International Institute for Applied System Analysis (AT) did a lot of analysis and publications on the data from more than a decade of remote sensing measurements at Zurich/CH. Their report highlighted that high in-use NO_x emissions from diesel vehicles were identified with remote sensing programs. Furthermore, for Euro 2 and Euro 3 diesel technology deterioration of NO_x emission cleaning systems were identified, while Euro 1 and Euro 4 technologies seem to be stable. (Borken-Kleefeld & Chen, 2015; Chen & Borken-Kleefeld, 2014; Chen & Borken-Kleefeld, 2016).
- Sweden: IVL Swedish Environmental Research Institute (SE): IVL has already a long history with remote sensing (Sjödin & Jerksjö, 2008). Martin Jerksjö and Åke Sjödin from IVL ran 5 programs since 2007 on several on-road emission measurements in Sweden. The latest program aimed more than 30.000 vehicles in the period September/October 2016. For 2017-2018 IVL will focus on Euro 6 and CNG heavy duty buses.
- Spain: RSLab (Remote Sensing Laboratory) and CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas) (E): They executed a Remote sensing project CORETRA commissioned by the Spanish Ministry for Environment in 2014/2015.
- United Kingdom: Universities in the UK such as King's College London, University of Leeds, Newcastle University and University of York (UK) had campaigns where they used the FEAT instrument from the University of Denver for two 6-week campaigns on six locations in London and Oxford. They were interested in total NO_x, NO_2 and NH_3, controlled test track conditions and a comparison with the RSD4600 remote sensing device from Opus Inspection. Also they found evidence concerning higher NO_x emissions from passenger cars and light duty vehicles. (Carslaw, et al., 2011a; Carslaw, et al., 2011b; Carslaw & Rhys-Tyler, 2013).

Most of the information on European Remote Sensing programs was gathered during the 1st European On-Road Emission Remote Sensing Workshop, 6-7 September 2016, Gothenburg, Sweden.

Recently Hager Environmental & Atmospheric Technologies (H.E.A.T.) developed EDAR (Emission Detection and Reporting), a laser-based technology capable of remotely detecting and measuring the pollutants emitted by in-use-vehicles. Independent studies on this equipment were not found. Denis, Budd, Hager & Hager (2015) described the equipment. The EDAR system is an unmanned, automated vehicle emissions measurement system, which collects data on four pollutants (CO, CO2, NO_x and HC). The gas sensor looks down from above and emits a sheet of invisible laser light from above that can unambiguously measure specified molecules emitted from any vehicle that breaks the beam. EDAR measures the entire exhaust plume as the vehicle passes allowing for determination of the mass emission rates of the vehicle.

The system includes:

- an eye-safe laser-based infrared gas sensor;
- a vehicle speed and acceleration sensor;
- a system to measure current weather conditions;
- a license plate recognition camera.

The 2014 On-Road Vehicle Survey from the Connecticut Vehicle Inspection Program (Denis, Budd, Hager & Hager, 2015) identified with the EDAR equipment a small percentage of the vehicles as high emitters (1.7% of the final sample). High emitting vehicles were identified as those exceeding thresholds used in earlier remote sensing studies (500 ppm HC, 3% CO, 2,000 ppm NO).

The OHMS, On-road Heavy-duty Emissions Monitoring System, was developed as an outgrowth of remote sensing techniques by the University of Denver. This OHMS system is described by Johnson, J. (2015) in his presentation for the 2015 PEMS International Workshop. Photos and schemes could be found of the partially enclosed tunnel-like structure where the system collects the exhaust emissions while the vehicle is running through this structure. The system measures black carbon emissions (BC), Total PM particulate numbers (PN) and particulate mass, as well as the gaseous pollutants CO, CO_2, THC, NO and NO_x. In the study from the Texas A&M Transportation Institute (2013) a good correlation is shown between OHMS measurements and the PEMS data for stop and go testing (R^2 = 0.8081).

5. Lab tests results

5.1. Lab Tests by TÜV NORD

5.1.1. Test vehicle and conditions

Both variants of the test cycle were driven with PEMS on a test track. No trouble codes were detected. For preconditioning ca. 11 km were driven at 90 km/h. The ambient temperature was 3,8°C and the ambient pressure 1028 mbar.

Figure 49 – Test vehicle TÜV NORD.

VIN:	JTMWPREV10D008969
Manufacturer:	Toyota
Type:	XA3(a)
Trade name:	RAV4
Engine type:	N47C20A
Capacity:	1995 cm^3
Engine power:	105 kW
Abgasnorm:	EU6
Typeapproval:	e6*2001/116*0105*15
Emission typeapproval:	e6*715/2007*2015/45W*0181*00
Registration date:	-
Mileage:	56 km
Gear box:	manual, 6-Gear

5.1.2. Test results

5.1.3. ASM2050 Variant 1 and 2 Tests

Figure 50 & 51 show the instantaneous NO_x Results of the tests in Variant 1 and Variant 2.

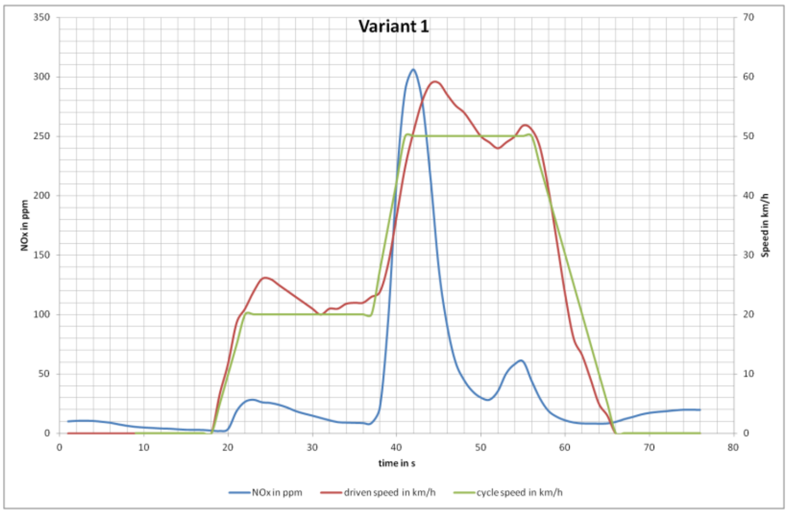


Figure 50 – Results ASM2050 Variant 1.

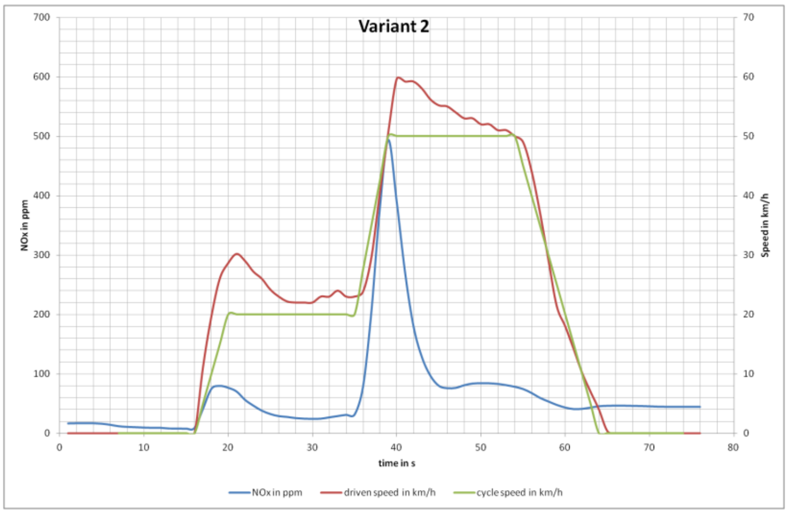


Figure 51 – Results ASM2050 Variant 2.

It is obvious that NO_x emissions increase during acceleration phases. In both tests increase during the acceleration from 20 km/h to 50 km/h in 2nd is higher than increase during acceleration from 0 km/h 20 km/h. During the second acceleration in Variant 1 test NO_x emissions increase up to 300 ppm and in Variant 2 test to almost 500 ppm.

Because of delay of speed signal it was difficult to follow the cycle speed.

5.1.4. "Spheretech" Test Procedure

Test cycle 1

Figure 52 shows the NOx emissions in relation to the motor speed. In the moment of acceleration, the Engine produces a small amount of load which leads to an increase of NOx.

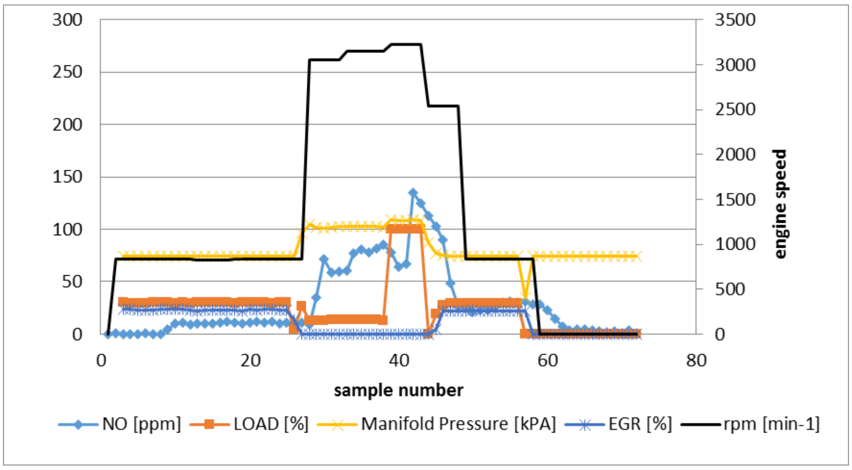


Figure 52 – NO_X emissions in relation to engine speed.

Test cycle 2

Figure 53 shows the same behavior of the engine. NOx emissions increase when the engine speed increases. The short delay between the increase of NOx and the increase of the engine speed is the result of the working section of the measurement system.

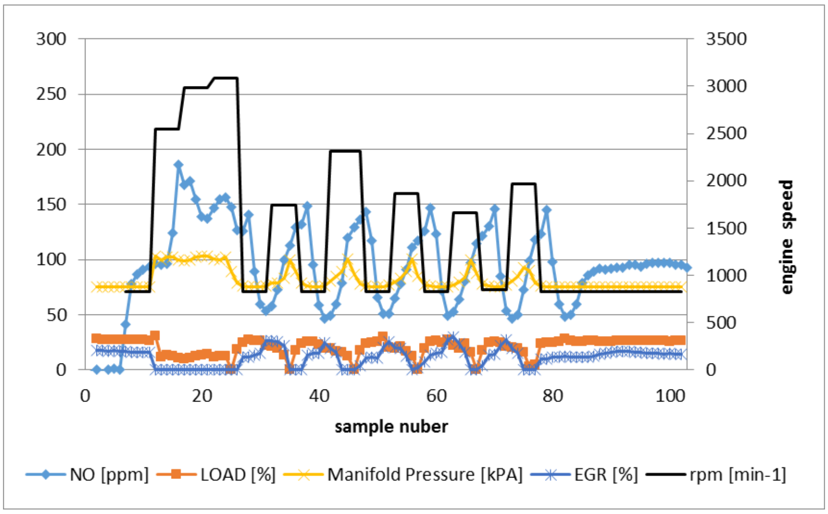


Figure 53 – NO_X emissions in relation to engine speed.

The BOSCH analyzer showed suitable NOx results. With the both of the Bosch procedures you can see the increase of NOx when the engine accelerates. In Both cases the EGR rate is decreased in order to make the combustion more effective and to spare fuel. The negative effect is that the combustion temperature increases and in combination with an increase of the engines load the emission of NOx increases.

In general this Method is able to measure even small increase of NOx even by this small amount of load. The problem is to differentiate between the increase of NOx because of the engines dynamic or because of a broken catalytic system.

5.1.5. Summary and Outlook

NOx emissions are in the focus of environmental policy. Therefore a method for evaluating nitric oxides during the periodic emission test is essential. Within the SET 2 project several methods for judging NOx emission during PTI are examined.

The analyzers used at TÜV NORD showed useful results, the accuracy seems to be adequate for evaluating NOx emissions during periodic emission tests.

For producing engine load, tests on road or test tracks are not necessarily needed. For reasons of better repeatability we prefer ASM2050 tests on chassis dynamometer. Although NOx emissions are produced especially at high engine loads and high temperatures within the combustion chamber also the BOSCH method seems to deliver suitable NOx values by using idle and high idle speeds without using a dynamometer.

There has to be a measurement campaign to evaluate the results. A wide range of cars should be tested without and with malfunction of exhaust aftertreatment systems. After evaluation of data there has to be a decision on a limit of NO_x emission in ASM2050 cycle or idle tests.

Future tasks:

- Comparison of OBD read out (fault codes, RC Status, status information) versus the tailpipe emission test
- Selection of suitable test methods including method of engine load setting
- Field test of selected test methods
- Definition of suitable thresholds for NOx
- Compile a precise recommendation including a cost-benefit analysis

5.2. Lab Tests by TÜV SÜD

5.2.1. Test conditions

Four different vehicles were used by the TÜV SÜD lab tests. The complete data set of these individual vehicles are here listed. The main differences of which are listed in Table 4. The vehicles differ both in their emission standard (Euro 5 or 6), as well as in their transmission type (automatic or manual) and continue in their capacity or their number of cylinders (four or six cylinders). In contrast, all four vehicles are equipped with an exhaust gas recirculation (EGR) valve, a diesel particulate filter (DPF) and a NOX storage catalytic converter (NSC).

Vehicle	Transmission Type	Capacity / number of cylinders	Emission Class	Drive	Introduced error
1	Automatic	1.968 / 4	Euro 5	Four-wheel	None
2	Manual	1.598 / 4	Euro 6	Front	LMM
3	Manual	1.598 / 4	Euro 6	Front	AGR
4	Automatic	2.993 / 6	Euro 6	Rear	AGR

Table 20 – Test vehicles TÜV SÜD.

In the case of vehicle 1 with which the ASM2050 cycle, due to the four-wheel drive, was traced on an all-wheel dynamometer, only one measurement could be carried out with a non-manipulated vehicle condition. For the remaining three vehicles, either the air mass meter (LMM) or the EGR valve was disconnected. To determine whether a noticeably higher nitrogen oxide emissions can be measured. Vehicle 2 was initially measured in the intact condition and then passed through both test methods again with a staked air mass meter (LMM). Disconnecting the LMM causes the engine to operate with a different composition of air and diesel. This corresponds to the error "Fat operation" in the measurement of AVL DiTEST GmbH. For vehicles 3 and 4, the EGR valve was disconnected after measuring the AVL and ASM2050 procedures in an intact vehicle condition. This was in contrast to vehicle 2 easily accessible from the top of the engine compartment. In contrast to the measurements of the AVL DiTEST GmbH, it was unfortunately not possible to determine the position after disconnecting the EGR valve. However, based on the following test results, the position of the EGR valve can be estimated. The following environmental conditions were present in the exhaust gas laboratory TÜV Hessen in Pfungstadt:

- Temperature: 23 ° C (prescribed temperature for the conditioning hall)
- Air pressure: 1.000 mbar (Pfungstadt lies at an altitude of 105 m)
- Real humidity: 55%

In order to make the measurement results more comparable, a portable emission measurement system (PEMS) from the manufacturer AVL LIST GmbH was used for both methods for nitrogen oxide measurement. This model was the type AVL 492 GAS PEMS IS. As a rule, a PEMS measuring device is mounted to the vehicle on the trailer hitch, as shown in Figure 16, in order to be able to carry out nitrogen oxide measurements under real conditions while driving on the road. In this case, however, it was a stationary PEMS meter, as measurements were taken on a chassis dynamometer. With a five-gas PEMS, not only nitrogen oxides (NO and NO2 are measured individually), but also CO, CO2 and O2 are measured.

Vehicle 1:

Fahrzeugdaten:	Zulassungsbescheinigung Teil I	Audi A4 Allroad 2.0 TDI (Diesel)
Herstellerschlüsselnummer (HSN)	2.1	0588 (Audi)
Typschlüsselnummer (TSN)	2.2	ASV 00084 (8K)
Fahrgestellnummer (VIN)	E	WAUZZZ8K2FAxxxxxx
Getriebeart	-	Automatik
Zul. Gesamt-/Leergewicht	F.2/G	2440/1745 kg
Wegstreckenzähler	-	19.536 km
Erstzulassung	B	09.12.2014
Emissionsklasse	14/14.1	Euro 5/35J0
EG-Typgenehmigung o. ABE	K	e1*2001/0430*33
Abgasnachbehandlungssysteme	-	AGR/DPF/NSC
Leistung	P.2	130 kW
Hubraum	P.1	1968 cm^3
Fahrzeugklasse	J/4	M1/AC
Angetriebene Achsen	9	Vorder- und Hinterachse
Zylinderanzahl	-	4

Table 21 – Fahrzeugdaten Audi A4 Allroad 2.0 TDI

Vehicle 2:

Fahrzeugdaten:	Zulassungsbescheinigung Teil I	Audi A3 1.6 TDI (Diesel)
Herstellerschlüsselnummer (HSN)	2.1	0588 (Audi)
Typschlüsselnummer (TSN)	2.2	AYB 00058 (8V)
Fahrgestellnummer (VIN)	E	WAUZZZ8V1GAxxxxxx
Getriebeart	-	Manuell
Zul. Gesamt-/Leergewicht	F.2/G	1820/1335 kg
Wegstreckenzähler	-	14.363 km
Erstzulassung	B	31.03.2016
Emissionsklasse	14	EURO 6/36W0
EG-Typgenehmigung o. ABE	K	e1*2007/46*0607*19
Abgasnachbehandlungssysteme	-	AGR/DPF/NSC
Leistung	P.2	81 kW
Hubraum	P.1	1.598 cm^3
Fahrzeugklasse	J/4	M1/AB
Angetriebene Achsen	9	Vorderachse
Zylinderanzahl	-	4

Table 22: Fahrzeugdaten Audi A3 1.6 TDI

Vehicle 3:

Fahrzeugdaten:	Zulassungsbescheinigung Teil I	Opel Meriva 1.6 TDI (Diesel)
Herstellerschlüsselnummer (HSN)	2.1	0035 (Opel)
Typschlüsselnummer (TSN)	2.2	00000000
Fahrgestellnummer (VIN)	E	W0LSH9EUXG4xxxxxx
Getriebeart	-	Manuell
Zul. Gesamt-/Leergewicht	F.2/G	1543/2040 kg
Wegstreckenzähler	-	9.200 km
Erstzulassung	B	31.03.2015
Emissionsklasse	14/14.1	Euro 6/36W0
EG-Typgenehmigung o. ABE	K	-
Abgasnachbehandlungssysteme	-	AGR/DPF/NSC
Leistung	P.2	100 kW
Hubraum	P.1	1.598 cm^3
Fahrzeugklasse	J/4	01/0200
Angetriebene Achsen	9	Vorderachse
Zylinderanzahl	-	4

Table 23: Fahrzeugdaten Opel Meriva 1.6 TDI

Vehicle 4:

Fahrzeugdaten	Zulassungsbescheinigung Teil I	BMW 530d (Diesel)
Herstellerschlüsselnummer (HSN)	2.1	0005 (BMW)
Typschlüsselnummer (TSN)	2.2	BGD 001111 (5K)
Fahrgestellnummer (VIN)	E	WBA5K1101Dxxxxxx
Getriebeart	-	Automatik
Zul. Gesamt-/Leergewicht	F.2/G	2470/1895 kg
Wegstreckenzähler	-	57.197 km
Erstzulassung	B	06.05.2015
Emissionsklasse	14/14.1	Euro 6/36W0
EG-Typgenehmigung o. ABE	K	e1*2007/46*0455*10
Abgasnachbehandlungssysteme	-	AGR/DPF/NSC
Leistung	P.2	190 kw
Hubraum	P.1	2.993 cm^3
Fahrzeugklasse	J/4	M1/AC
Angetriebene Achsen	9	Hinterachse
Zylinderanzahl	-	6

Table 24: Fahrzeugdaten BMW 530d

5.2.1.1. Evaluations of the AVL test cycle

Messung:	Fahrzeugzustand:	NO_X in ppm:				
		1	2	3	4	5
1	in Ordnung	155,7	83,7	118,0	128,2	94,0
2	in Ordnung	110,1	87,9	91,5	153,7	85,9
3	in Ordnung	83,3	92,0	83,4	98,4	86,9
4	in Ordnung	141,7	121,8	102,2	93,7	94,2
6	in Ordnung	143,3	140,6	122,2	119,4	119,3

Table 25: Fahrzeug 1 Audi A4 Allroad Quattro AVL Messung

Messung:	Fahrzeugzustand:	NO_X in ppm:				
		1	2	3	4	5
1	in Ordnung	145,6	86,0	95,5	97,8	96,8
3	in Ordnung	100,7	113,8	117,7	117,4	115,3
4	LMM abgesteckt	257,4	198,0	207,0	205,1	231,6
5	LMM abgesteckt	256,0	204,2	194,3	203,6	184,5

Table 26: Fahrzeug 2 Audi A3 AVL Messung

Messung:	Fahrzeugzustand:	NO_X in ppm:				
		1	2	3	4	5
1	in Ordnung	190,8	152,3	130,2	118,4	114,2
2	in Ordnung	166,0	118,9	102,4	117,5	102,0
4	AGR-Ventil abgesteckt	216,3	162,4	187,3	142,2	157,1
5	AGR-Ventil abgesteckt	236,1	146,5	151,1	148,3	144,7

Table 27: Fahrzeug 3 Opel Meriva AVL Messung

Messung:	Fahrzeugzustand:	NO_X in ppm:				
		1	2	3	4	5
1	in Ordnung	155,7	100,0	101,4	111,1	-
3	in Ordnung	135,2	105,8	98,0	101,6	120,0
4	AGR-Ventil abgesteckt	171,5	150,6	156,6	151,8	-
5	AGR-Ventil abgesteckt	182,8	151,1	136,2	120,0	127,6
6	AGR-Ventil abgesteckt	179,2	127,3	133,8	127,1	149,5
7	AGR-Ventil abgesteckt	180,4	132,7	135,8	142,0	-
8	AGR-Ventil abgesteckt	180,0	160,7	132,7	142,2	-
10	AGR-Ventil abgesteckt	179,0	146,0	175,5	-	-

Table 28: Fahrzeug 4 BMW 530d AVL Messung

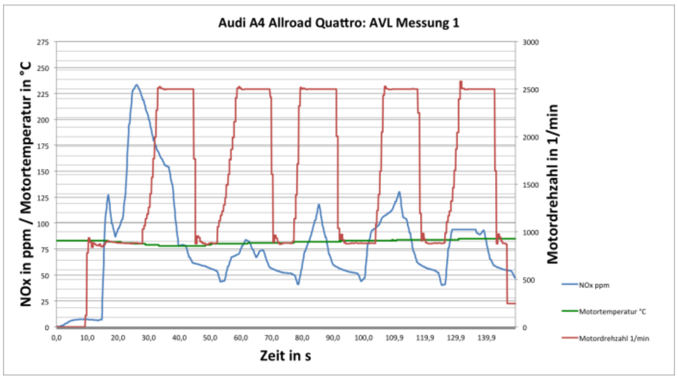


Figure 54: Audi A4 Allroad Quattro AVL Messung 1

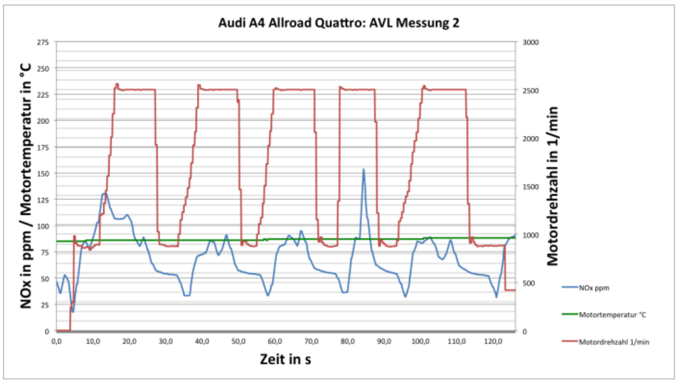


Figure 55: Audi A4 Allroad Quattro AVL Messung 2

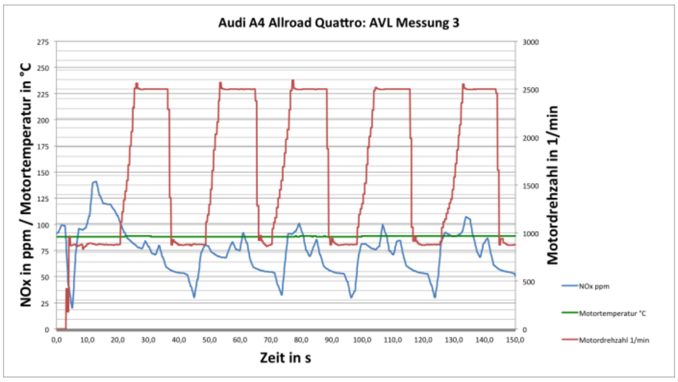


Figure 56: Audi A4 Allroad Quattro AVL Messung 3

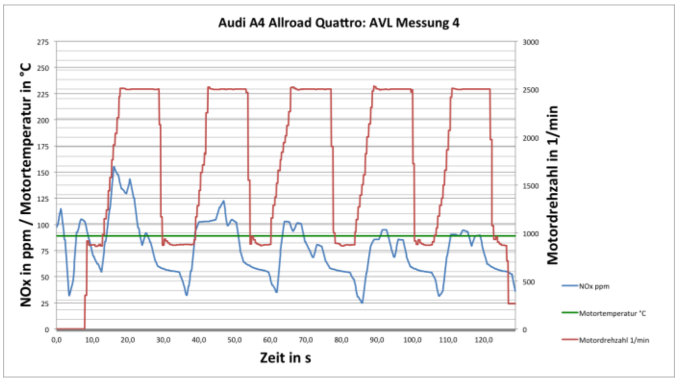


Figure 57: Audi A4 Allroad Quattro AVL Messung 4

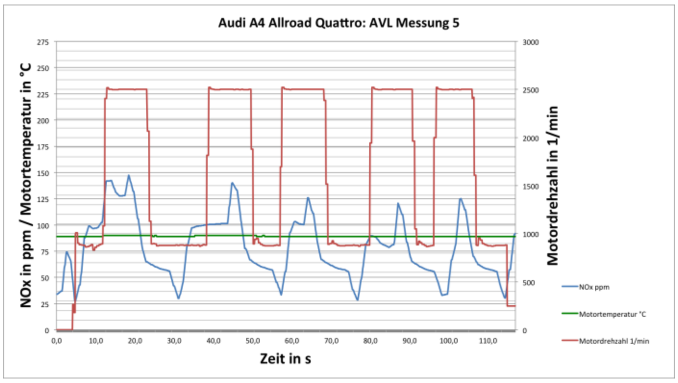


Figure 58: Audi A4 Allroad Quattro AVL Messung 5

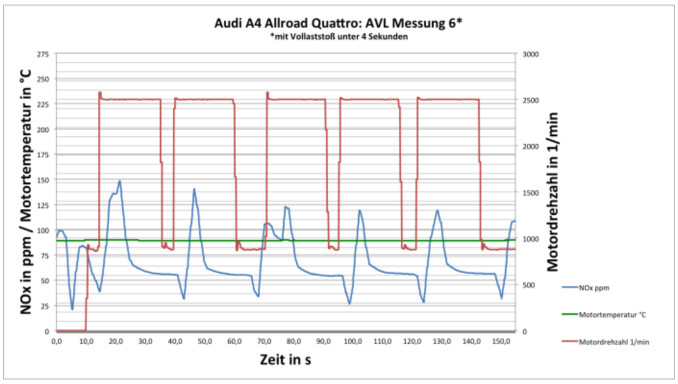


Figure 59: Audi A4 Allroad Quattro AVL Messung 6

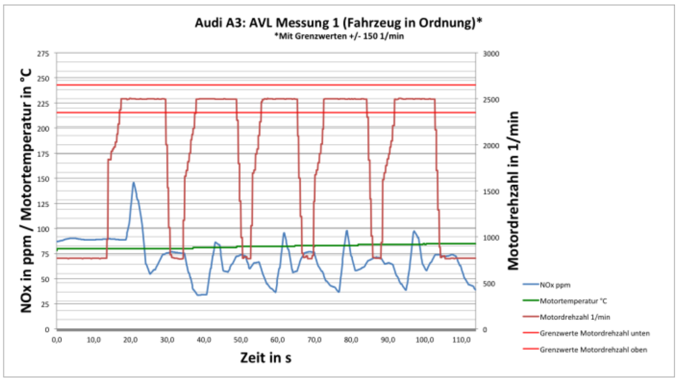


Figure 60: Audi A3 AVL Messung 1

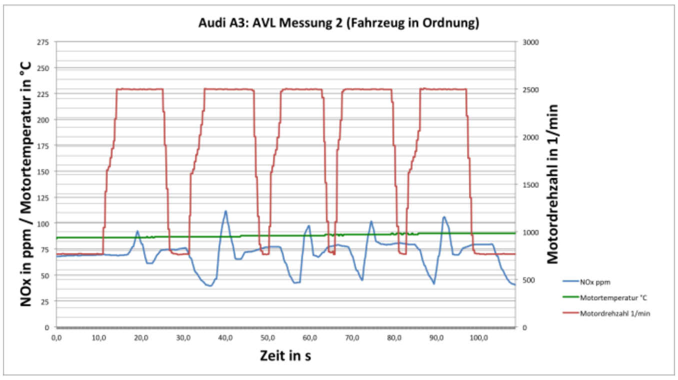


Figure 61: Audi A3 AVL Messung 2

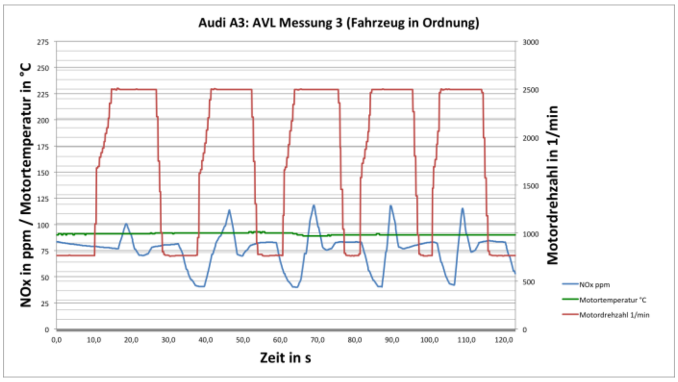


Figure 62: Audi A3 AVL Messung 3

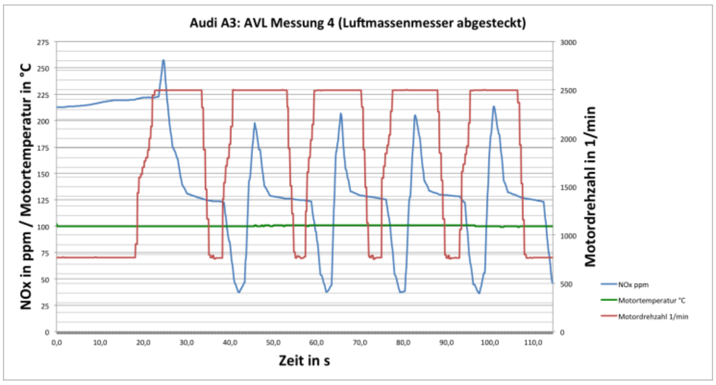


Figure 63: Audi A3 AVL Messung 4

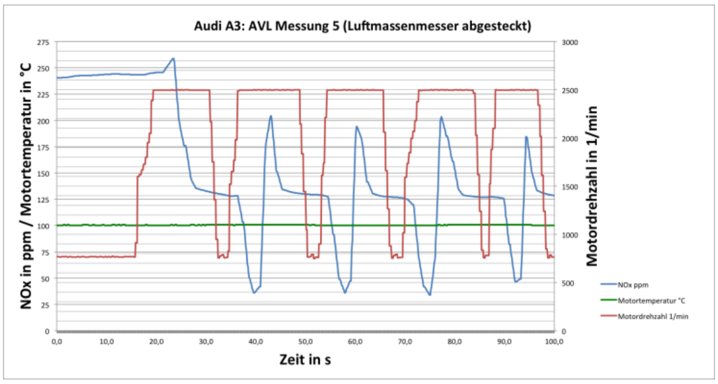


Figure 64: Audi A3 AVL Messung 5

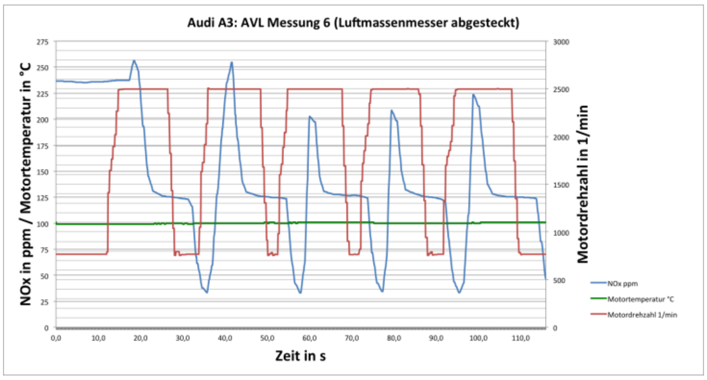


Figure 65: Audi A3 AVL Messung 6

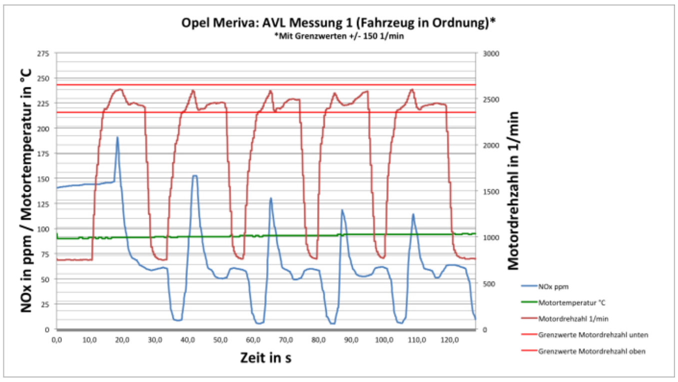


Figure 66: Opel Meriva AVL Messung 1

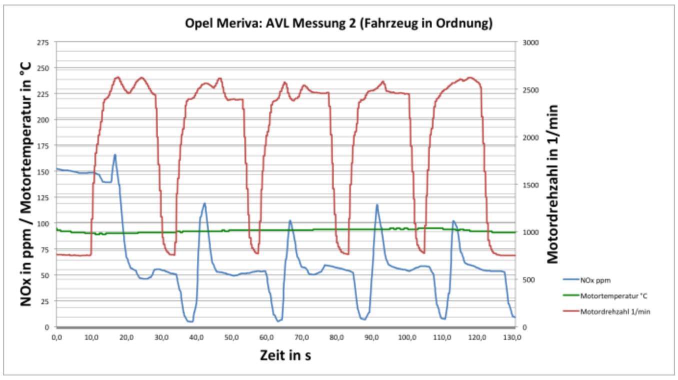


Figure 67: Opel Meriva AVL Messung 2

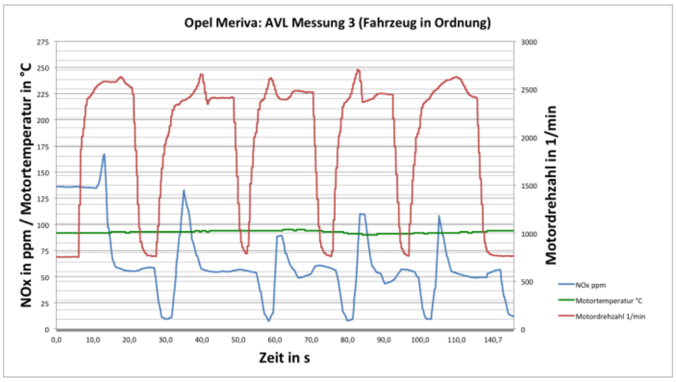


Figure 68: Opel Meriva AVL Messung 3

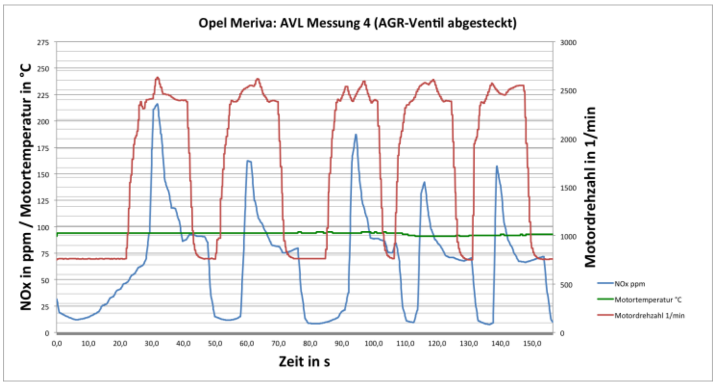


Figure 69: Opel Meriva AVL Messung 4

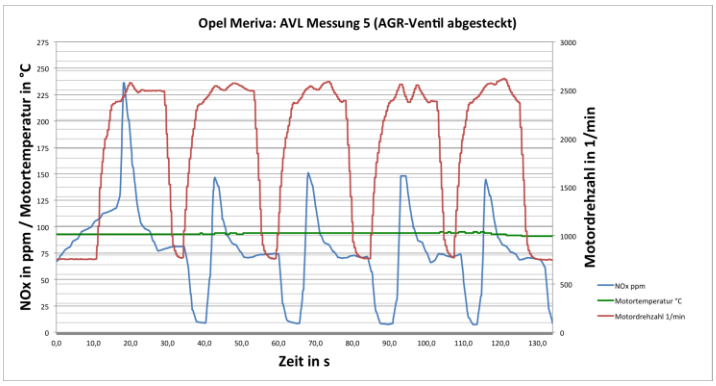


Figure 70: Opel Meriva AVL Messung 5

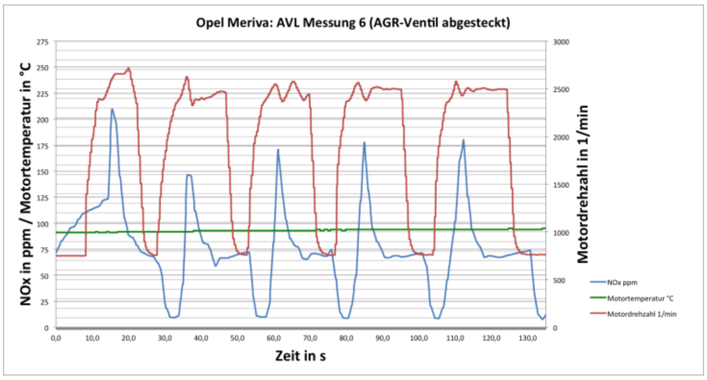


Figure 71: Opel Meriva AVL Messung 6

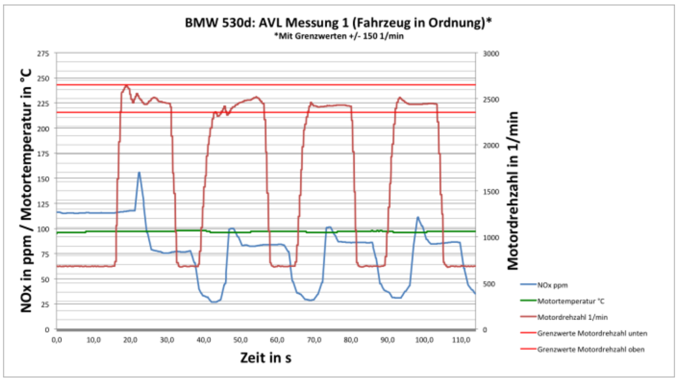


Figure 72: BMW 530d AVL Messung 1

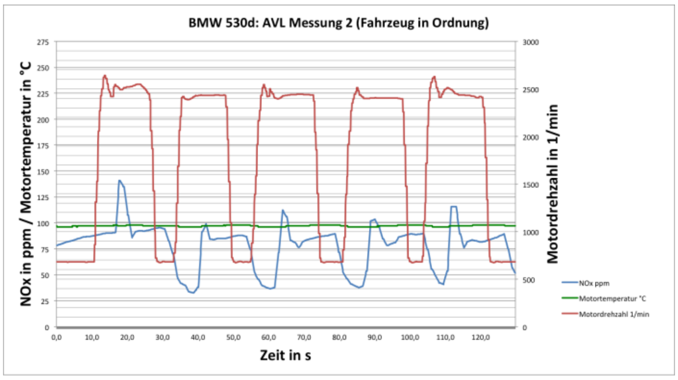


Figure 73: BMW 530d AVL Messung 2

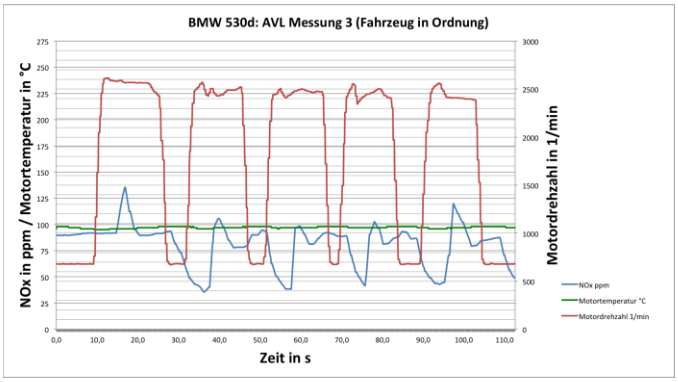


Figure 74: BMW 530d AVL Messung 3

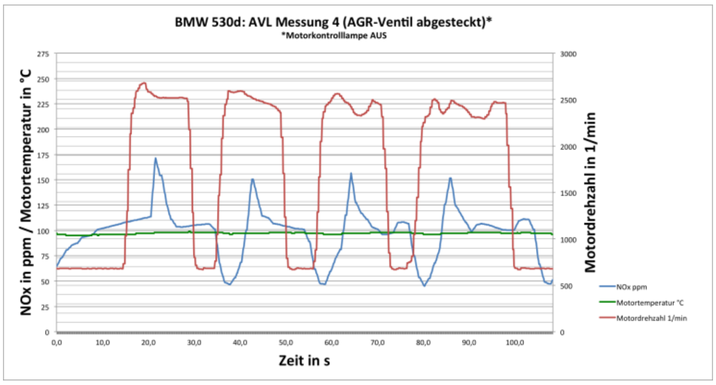


Figure 75: BMW 530d AVL Messung 4

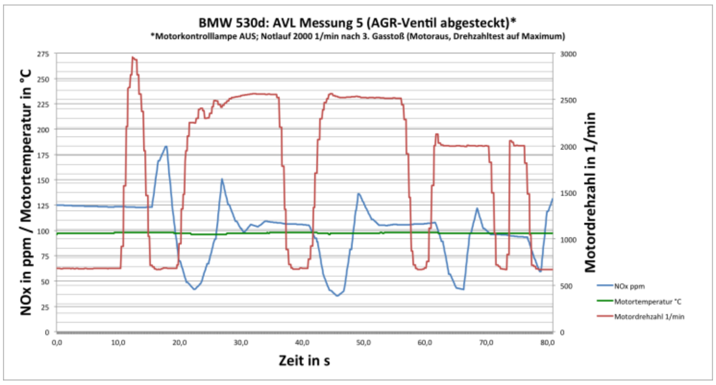


Figure 76: BMW 530d AVL Messung 5

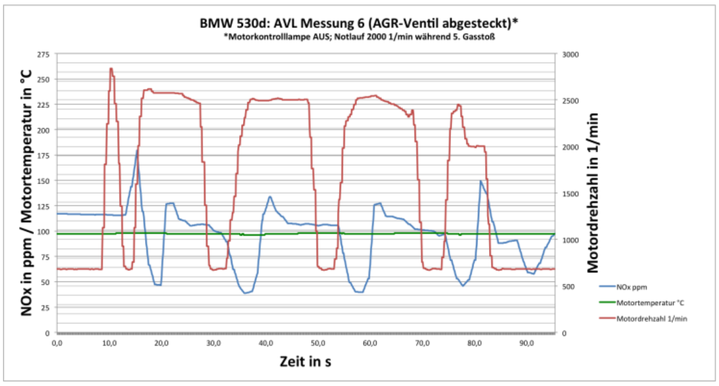


Figure 77: BMW 530d AVL Messung 6

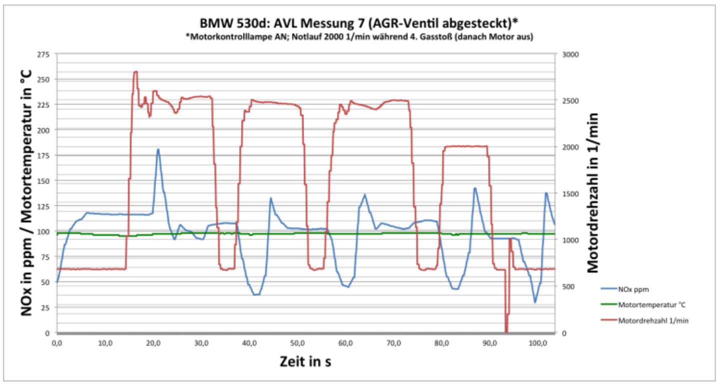


Figure 78: BMW 530d AVL Messung 7

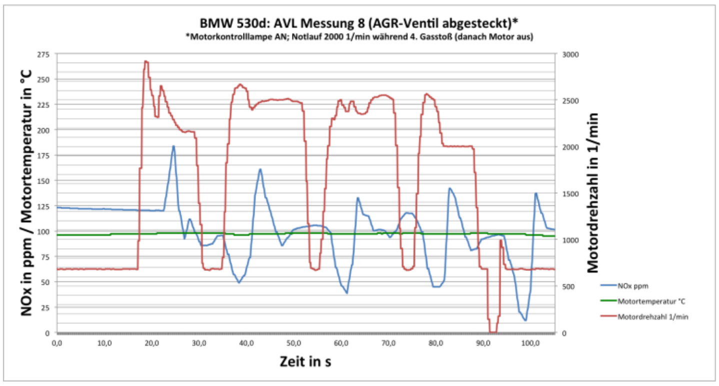


Figure 79: BMW 530d AVL Messung 8

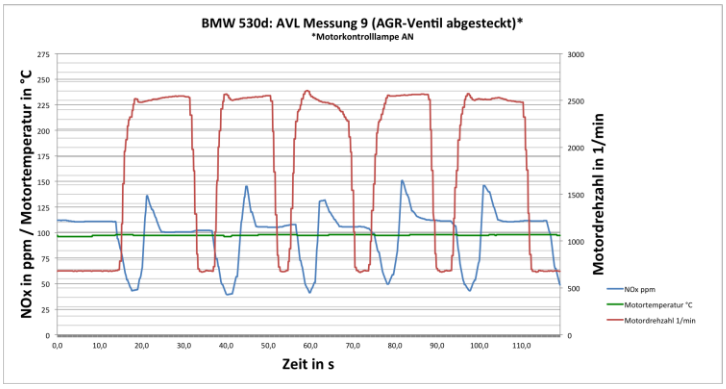


Figure 80: BMW 530d AVL Messung 9

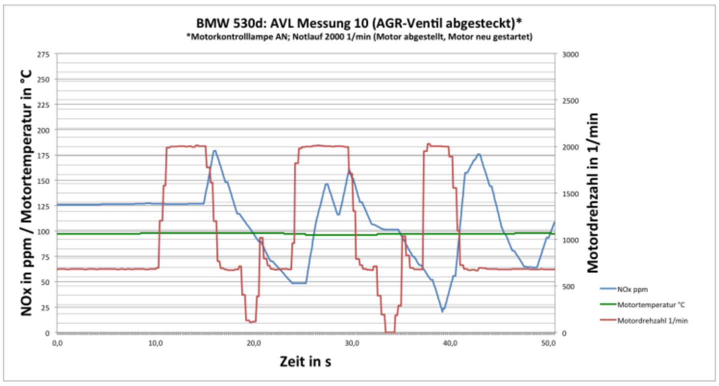


Figure 81: BMW 530d AVL Messung 10

5.2.2. Evaluations of the ASM2050 with and wihout failure

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
2	in Ordnung	173,4	664,0
3	Luftmassenmesser abgesteckt	461,2	766,3

Table 29: Fahrzeug 2 Audi A3 ASM2050 M12-Messung 2 und 3

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
1	in Ordnung	31,1	359,2
3	AGR-Ventil abgesteckt	208,1	641,7

Table 30: Fahrzeug 3 Opel Meriva ASM2050 M12-Messung 1 und 3

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
2	in Ordnung	157,0	356,0
4	AGR-Ventil abgesteckt	334,8	529,5

Table 31: Fahrzeug 4 BMW 530d ASM2050 M12-Messung 2 und 4

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
1	in Ordnung	184,1	552,4
3	Luftmassenmesser abgesteckt	592,5	668,1

Table 32: Fahrzeug 2 Audi A3 ASM2050 M123-Messung 1 und 3

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
1	in Ordnung	325,1	595,8
4	AGR-Ventil abgesteckt	198,3	619,1

Table 33: Fahrzeug 3 Opel Meriva ASM2050 M123-Messung 1 und 4

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
2	in Ordnung	124,1	299,5
3	AGR-Ventil abgesteckt	324,1	463,8

Table 34: Fahrzeug 4 BMW 530d ASM2050 M123 Messung 2 und 3

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
1	in Ordnung	175,0	463,0
4	AGR-Ventil abgesteckt	330,1	652,6

Table 35: Fahrzeug 4: BMW 530d ASM2050 A-Messung 1 und 4

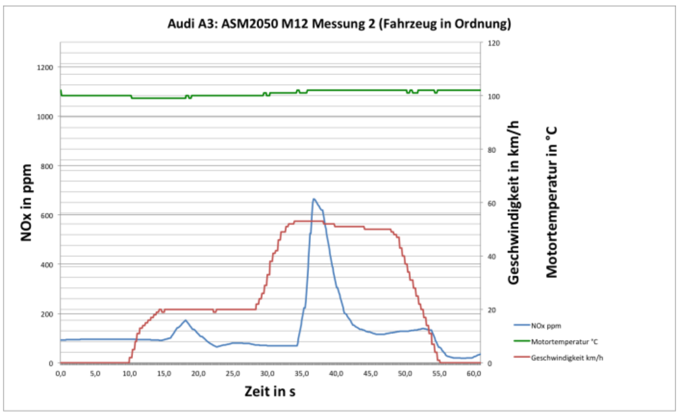


Figure 82: Audi A3 ASM2050 M12 Messung 2

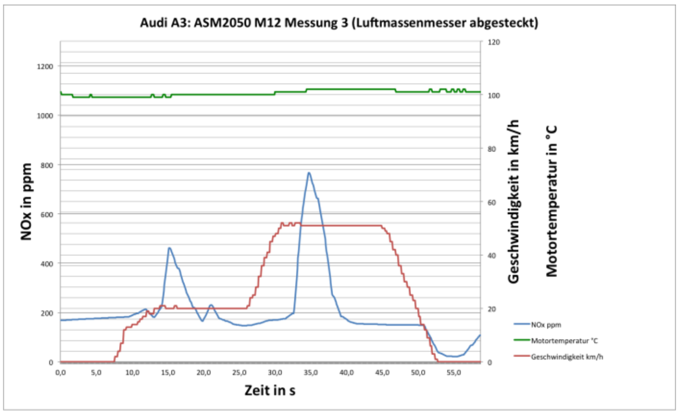


Figure 83: Audi A3 ASM2050 M12 Messung 3

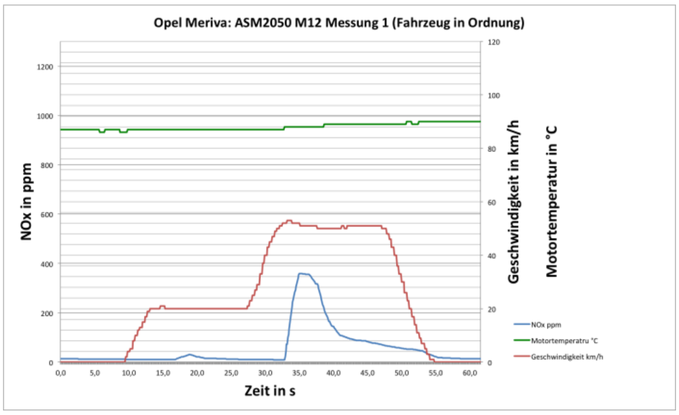


Figure 84: Opel Meriva ASM2050 M12 Messung 1

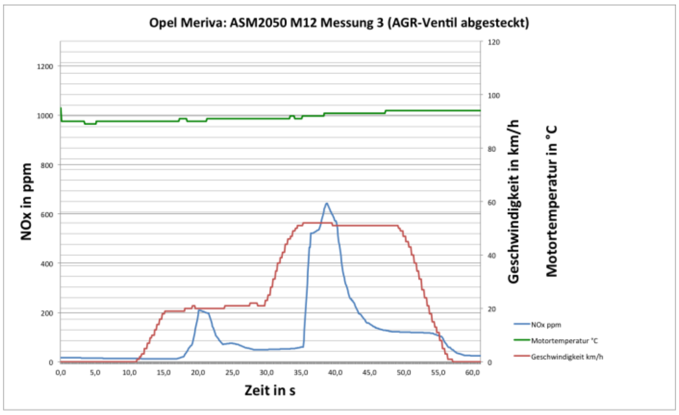


Figure 85: Opel Meriva ASM2050 M12 Messung 3

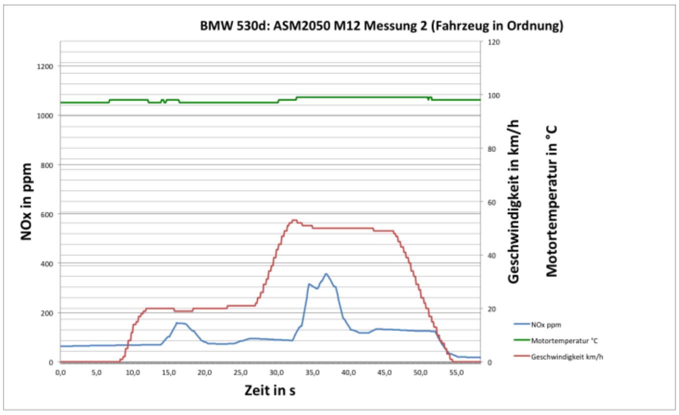


Figure 86: BMW 530d ASM250 M12 Messung 2

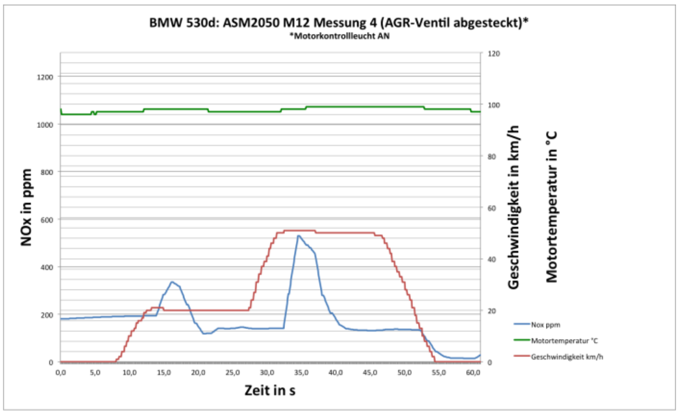


Figure 87: BMW 530d ASM2050 M12 Messung 4

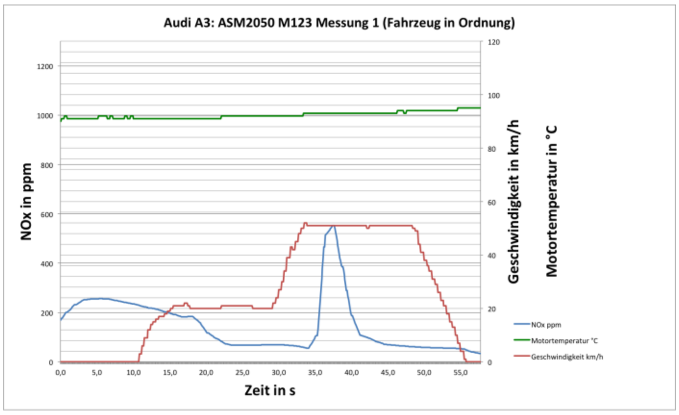


Figure 88: Audi A3 ASM2050 M123 Messung 1

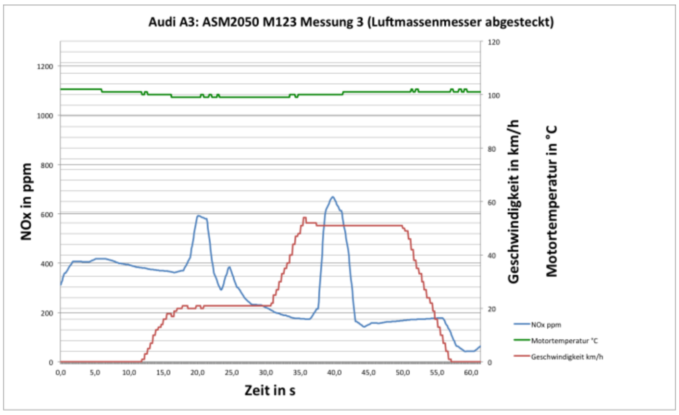


Figure 89: Audi A3 ASM2050 M123 Messung 3

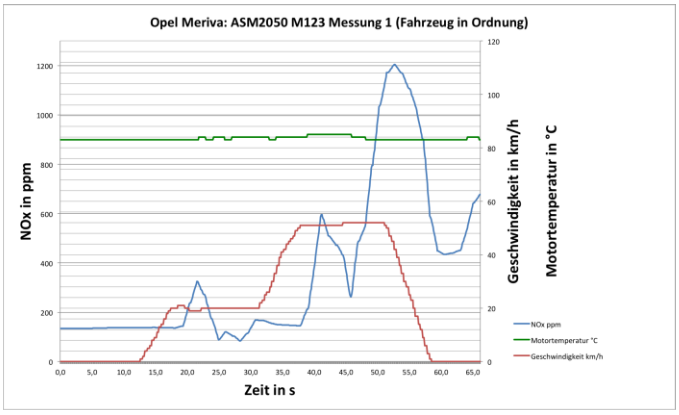


Figure 90: Opel Meriva ASM2050 M123 Messung 1

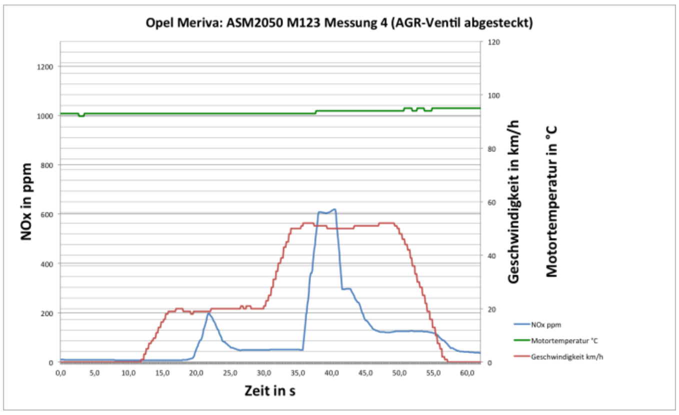


Figure 91: Opel Meriva ASM2050 M123 Messung 4

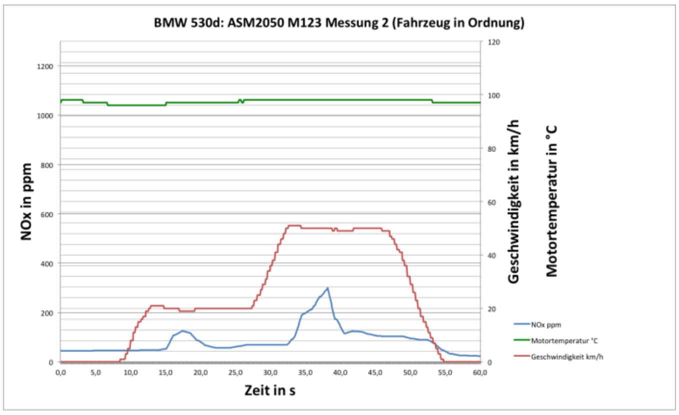


Figure 92: BMW 530d ASM2050 M123 Messung 2

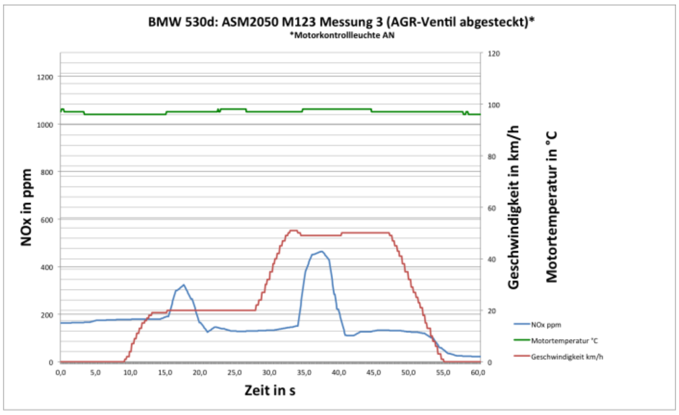


Figure 93: BMW 530d ASM2050 M123 Messung 3

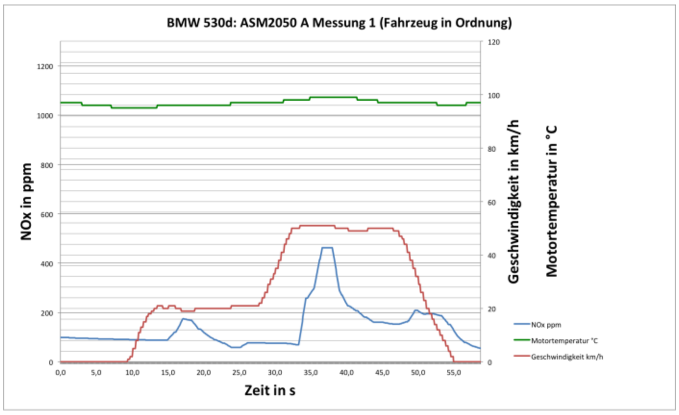


Figure 94: BMW 530d ASM2050 A Messung 1

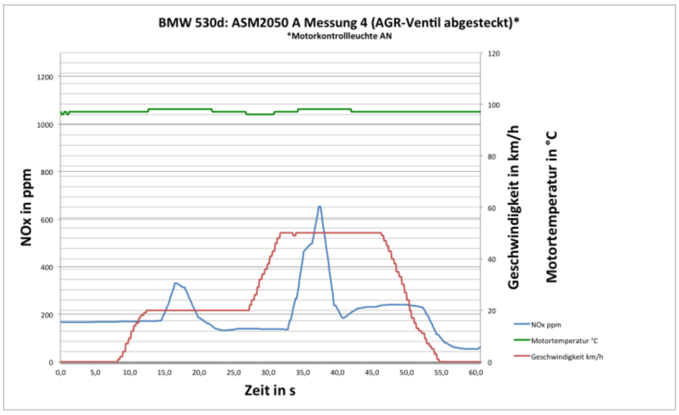


Figure 95: BMW 530d ASM2050 A Messung 4

5.2.3. Evaluations of ASM2050 variants

The tests results from above are completed with these results were the variants in acceleration during the ASM2050 cycle are shown.

Two variants of the ASM2050 cycle were described in the literature review (Pando, 2016).
Since vehicles with automatic transmission were also available for testing, a third variant was also added. In variant 1, the cycle is driven from the point T2 in second gear to the end. In variant 2, the second gear changes to third gear at point T4, so that the 50 km / h are driven in third gear. The third variant, which can be run exclusively with automatic transmission equipped vehicles, provides that the test cycle in selector lever position D (Drive) of the transmission is traversed from start to finish. Variant 1 and 2 are driven for vehicles with automatic transmission, depending on the equipment, in selector lever position M (manual) and either with the gear knob in the default gear position switched (M1, 2 or M1, 2, 3) or via shift paddles on the steering wheel.

The following differents variants are identified:

- ASM2050 M12 (Variant 1)
- ASM2050 M123 (Variant 2)
- AMS2050 A (Variant 3)

ASM2050 M12 (Variant 1)

Vehicle 1:

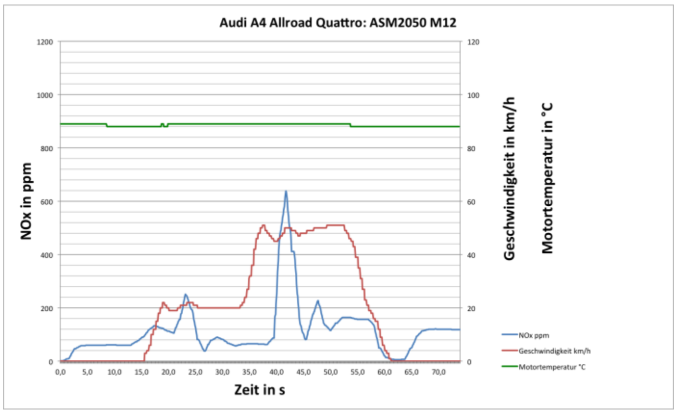


Figure 96: Audi Allroad Quattro: ASM 2050 M12

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
1	in Ordnung	250,7	638,5

Table 36: Audi Allroad Quattro: ASM2050 M12

Vehicle 2:

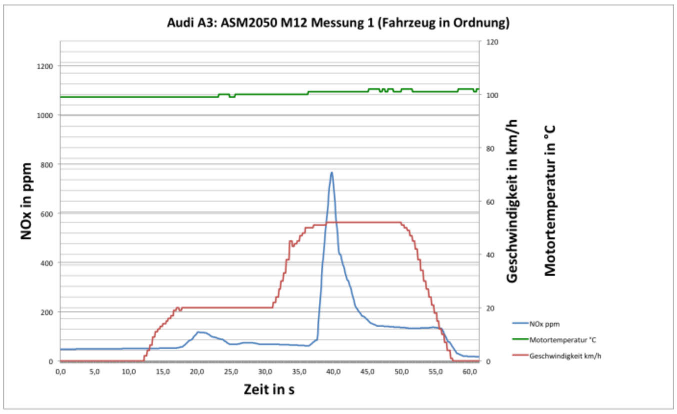


Figure 97: Audi A3 ASM2050 M12 Messung 1

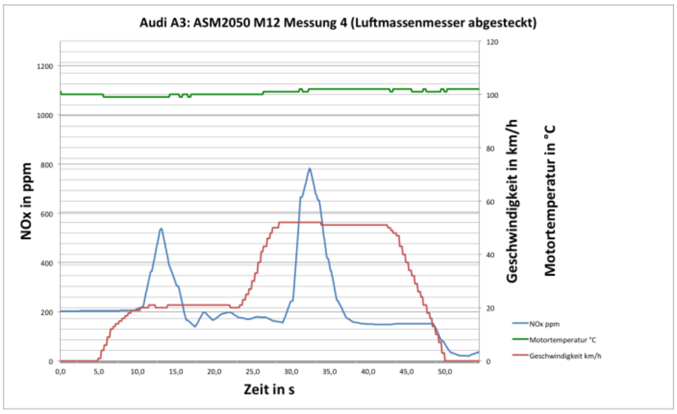


Figure 98: Audi A3 ASM2050 M12 Messung 4

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
1	in Ordnung	116,5	766,2
4	LMM abgesteckt	538,8	783,1

Table 37: BMW 530d ASM2050 M123 Messung 1 und 4

Vehicle 3:

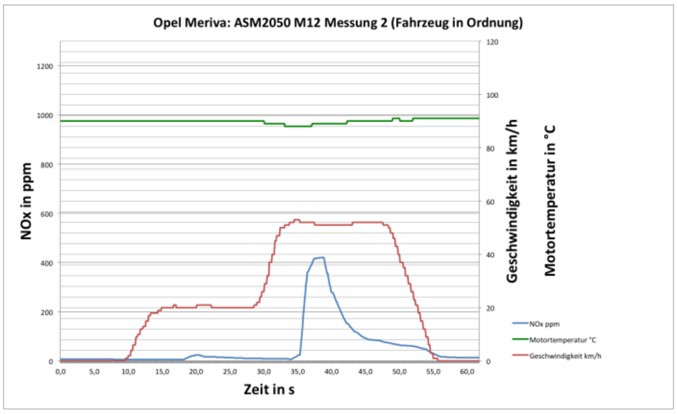


Figure 99: Opel Meriva ASM2050 M12 Messung 2

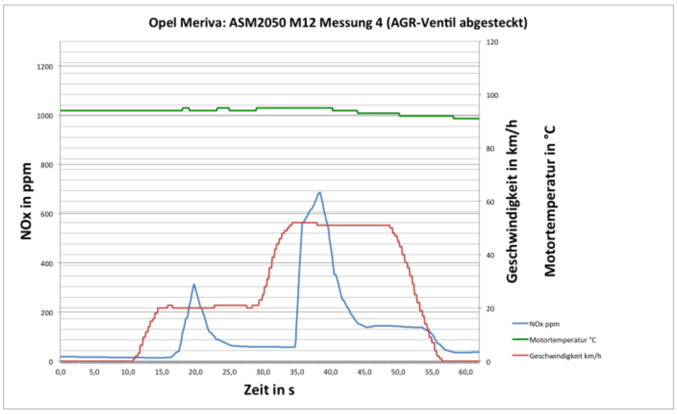


Figure 100: Opel Meriva ASM2050 M12 Messung 4

Messung:	Fahrzeugzustand	NO_x in ppm:	
		20 km/h	50 km/h
2	in Ordnung	24,3	420,9
4	AGR-Ventil abgesteckt	312,3	685,6

Table 38: Opel Meriva ASM2050 M12 Messung 2 und 4

Vehicle 4:

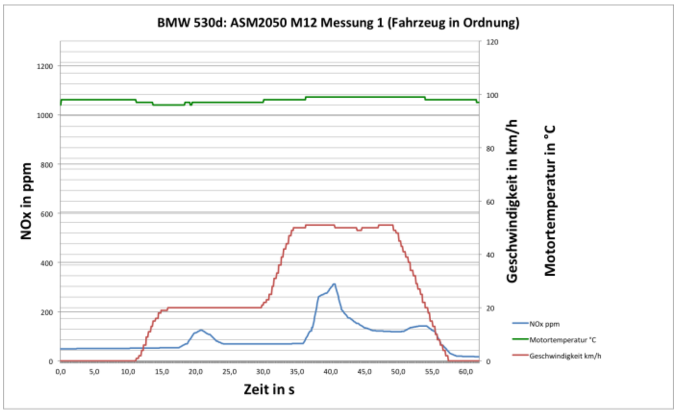


Figure 101: BMW 530d ASM2050 M12 Messung 1

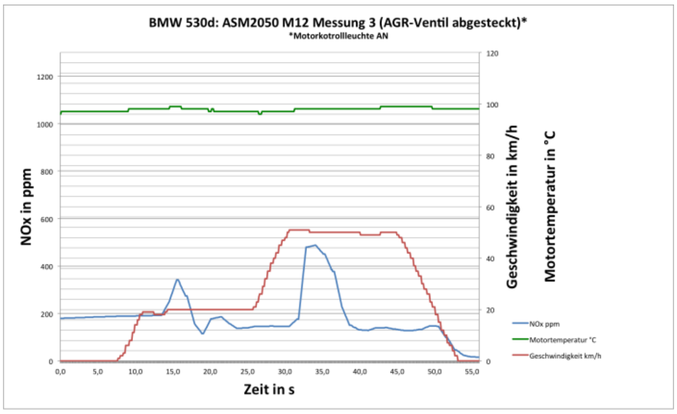


Figure 102: BMW 530d ASM2050 Messung 3

Messung:	Fahrzeugzustand:	NO_x in ppm:	
		20 km/h	50 km/h
1	in Ordnung	125,2	313,0
3	AGR-Ventil abgesteckt	342,3	487,5

Table 39: BMW 530d ASM2050 Messung 1 und 3

ASM2050 M123 (Variante 2)

Vehicle 1:

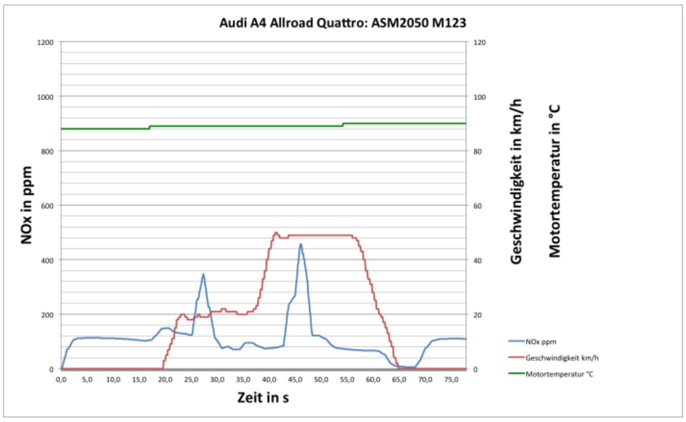


Figure 103: Audi A4 Allroad Quattro ASM2050 M123

Messung:	Fahrzeugzustand:	NO_x in ppm:	
		20 km/h	50 km/h
1	in Ordnung	99,8	304,6

Table 40: Audi A4 Allroad Quattro M123

Vehicle 2:

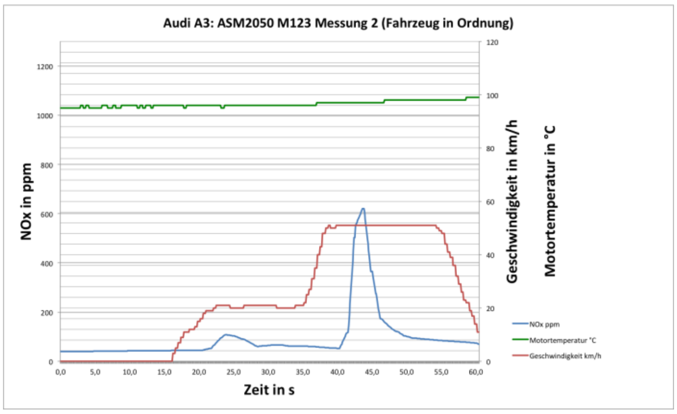


Figure 104: Audi A3 ASM2050 M123 Messung 2

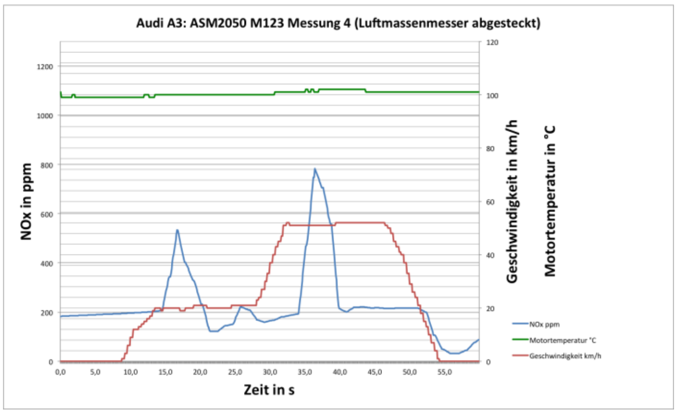


Figure 105: Audi A3 ASM2050 M123 Messung 4

Messung:	Fahrzeugzustand:	NO_x in ppm:	
		20 km/h	50 km/h
2	in Ordnung	108,0	620,6
4	Luftmassenmesser abgesteckt	534,1	782,8

Table 41: Audi A3 ASM2050 M123 Messung 2 und 4

Vehicle 3:

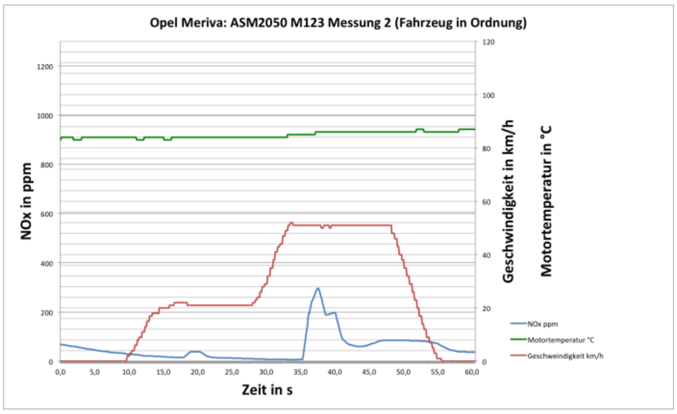


Figure 106: Opel Meriva ASM2050 M123 Messung 2

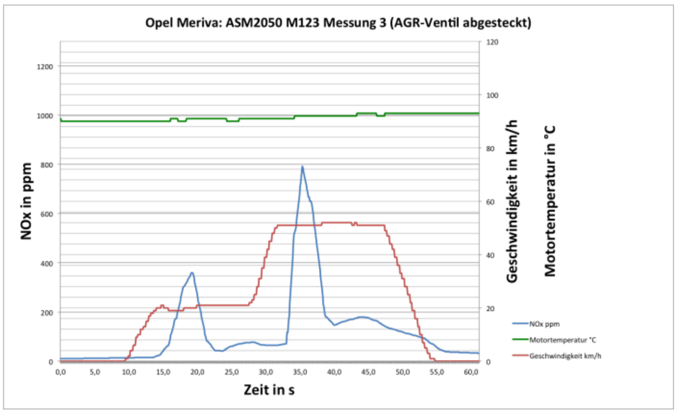


Figure 107: Opel Meriva ASM2050 M123 Messung 3

Messung:	Fahrzeugzustand:	NO_x in ppm:	
		20 km/h	50 km/h
2	in Ordnung	39,0	296,9
3	AGR-Ventil abgesteckt	358,7	729,2

Table 42: Opel Meriva ASM2050 M123 Messung 2 und 3

Vehicle 4:

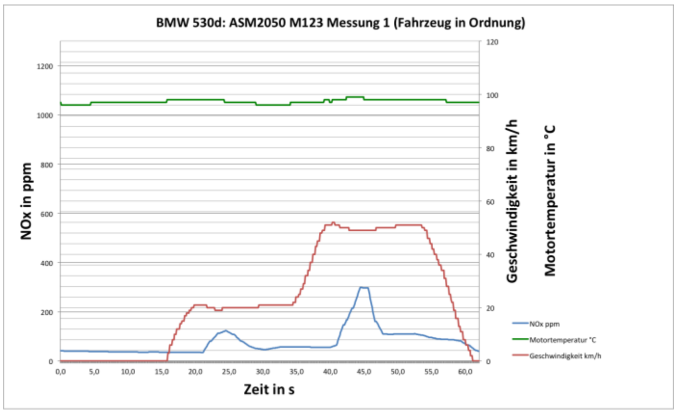


Figure 108: BMW 530d ASM2050 M123 Messung 1

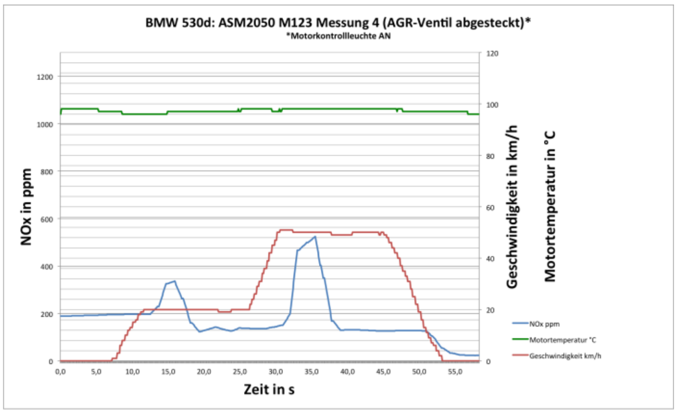


Figure 109: BMW 530d ASM2050 M123 Messung 4

Messung:	Fahrzeugzustand:	NO_x in ppm:	
		20 km/h	50 km/h
1	in Ordnung	123,0	297,7
4	AGR-Ventil abgesteckt	336,0	523,8

Table 43: BMW 530d ASM2050 M123 Messung 1 und 4

ASM2050 A (Variante 3)

<u>Vehicle 1:</u>

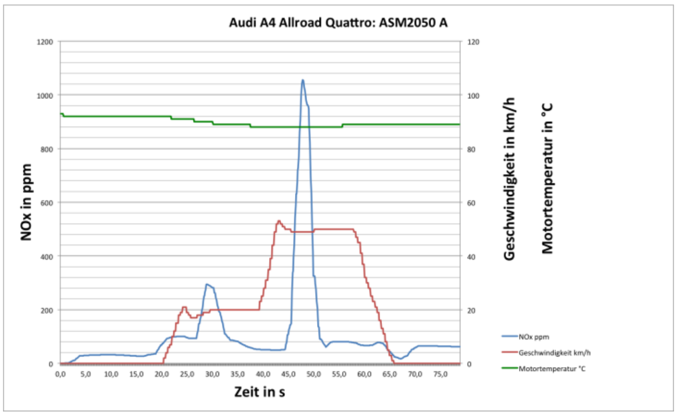


Figure 110: Audi A4 Allroad Quattro ASM2050 A

Messung:	Fahrzeugzustand:	NO_X in ppm:	
		20 km/h	50 km/h
1	in Ordnung	294,8	1053,4

Table 44: Audi A4 Allroad Quattro ASM2050 A

Vehicle 4:

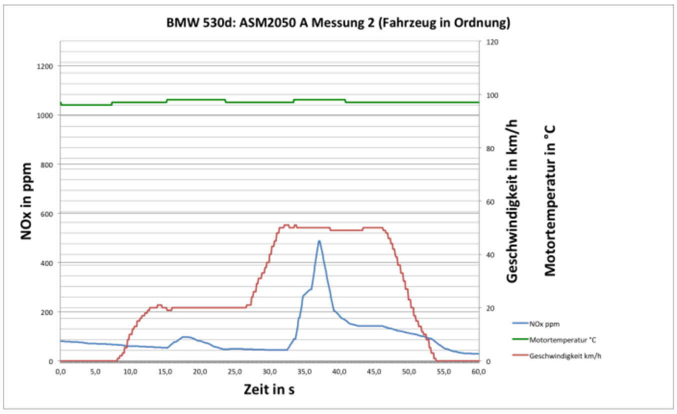


Figure 111: BMW 530d ASM2050 A Messung 2

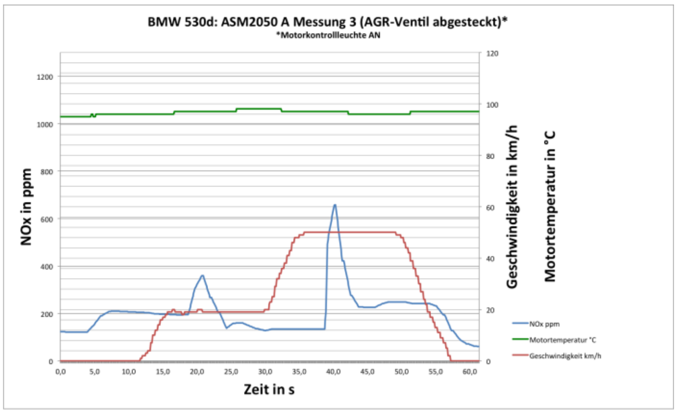


Figure 112: BMW 530d ASM2050 A Messung 3

Messung:	Fahrzeugzustand:	NO_x in ppm:	
		20 km/h	50 km/h
2	in Ordnung	97,3	486,8
3	AGR-Ventil abgesteckt	359,1	657,7

Table 45: BMW 530d ASM2050 A Messung 2 und 3

5.3. Lab Tests by DEKRA

5.3.1. Measurement devices

1. PEMS (Portable emission measurement system) → used as "reference"

manufacturer:	AIP (formally MAHA-AIP)
type:	Gas-PEMS
measuring principle for NOx	chemiluminescense detector (CLD)

2. 4-Gas-Analyzer (1)

manufacturer:	AVL DiTest
type:	Gas1000 with option NO (NOx)
measuring principle for NOx	1x electrochemical cell (paramagnetic) for NO (NOx is calculated)

3. 4-Gas-Analyzer (2)

manufacturer:	MAHA – Maschinenbau Haldenwang
type:	MET 6.3 with option NOx
measuring principle for NOx	1x electrochemical cell (paramagnetic) for NO 1x electrochemical cell (paramagnetic) for NO2

We used either 4-gas-analyzer (1) or (2), never both.

Additionally we used a **ECU diagnostic device** for recording of engine speed, vehicle speed, temperatures, … This device was depending on the vehicle/manufacturer.
It was a VCDS, AVL-DiTest "XDS 1000", or a TEXA "Axone"

For the cycles (ASM2050, DT80) we used a 4-wheel dyno. It was a "MSR500-2" from MAHA

5.3.2. Test vehicles

Vehicle No. 1

manufacturer:	Volkswagen (VW)
type:	Passat (3C)
engine type:	Diesel
engine displacement:	2,0 l (1,968 ccm)
rated power:	103 kW / 4.200 1/min
Gear:	automatic (VW DSC-system)
Date of 1st registration:	16.05.2011
odometer:	108.000 km ?
Euro class:	Euro 6a (N)
Engine code:	CFFB
Aftertreatment:	EGR, Oxi-Kat + DPF, SCR-System

Vehicle No. 2

manufacturer:	Volkswagen (VW)
type:	Polo (3R)
engine type:	Diesel
engine displacement:	1,6 l (1,682 ccm)
rated power:	66 kW / 4.200 1/min
Gear:	mechanical
Date of 1st registration:	27.01.2011
odometer:	103.400 km
Euro class:	Euro 5a (A)
Engine code:	CAYB
Aftertreatment:	EGR, Oxi-Kat + DPF

Vehicle No. 3

manufacturer:	KIA Motors (SK)
type:	Sportage 2,0 CRDi (QLE)
engine type:	Diesel
engine displacement:	1,9 l (1,855 ccm)
rated power:	100 kW / 4.000 1/min
Gear:	mechanical
Date of 1st registration:	31.03.2017
odometer:	3.500 km
Euro class:	Euro 6b (W)
Engine code:	?
Aftertreatment:	EGR, Oxi-Kat + DPF

Vehicle No. 4

manufacturer:	Mercedes
type:	E 220D (W212)
engine type:	Diesel
engine displacement:	2,0 l (1,950 ccm)
rated power:	143 kW / 3.800 1/min
Gear:	automatic
Date of 1st registration:	16.05.2017
odometer:	1.800 km
Euro class:	Euro 6c (ZD)
Engine code:	OM654
Aftertreatment:	EGR, Oxi-Kat + DPF (catalytically active), SCR-System

Vehicle No. 5

manufacturer:	BMW
type:	116 d (F20 , 1V71)
engine type:	Diesel
engine displacement:	1,6 l (1,496 ccm)
rated power:	85 kW / 4.000 1/min
Gear:	mechanical
Date of 1st registration:	12.01.2017
odometer:	3.200 km
Euro class:	Euro 6b (W)
Engine code:	B37D15U0 (3 cylinders
Aftertreatment:	EGR, DPF, LNT (Lean NOx Trap) / (NSC NOx Storage Catalyst)

5.3.3. Lab tests Vehicle 1

5.3.3.1. Installed failure

Vehicle No. 1 is a vehicle with Euro 6(a). It is equipped with a EGR, DOC+DPF and SCR-system.

The installed failure for this vehicle was to manipulate the EGR-system (See also the other vehicles 2 – 5), plus additionally the SCR catalyst was mechanical destroyed by 2 holes (diameter 15 mm) completely through both parts of the SCR catalyst.

Figure 113: installed failure vehicle 1

The OBD-System didn’t noticed this defects. But at “real driving”, mostly on motorway, the urea (AdBlue) consumption was pretty high, up to one tank filling (about 10 liters) per 1.000 km

5.3.3.2. ASM2050

Procedure:	**ASM2050**	
Vehicle:	**No.1**	(VW Passat, DOC+DPF, SCR, Euro 6)
Measurement:	**PEMS** (and other)	
Version:	1 / 2018.20.02	

1. Comparison: with/without defect

Some examples for driving cycles, record of NOx

1.1 Without defect (w/o defect)

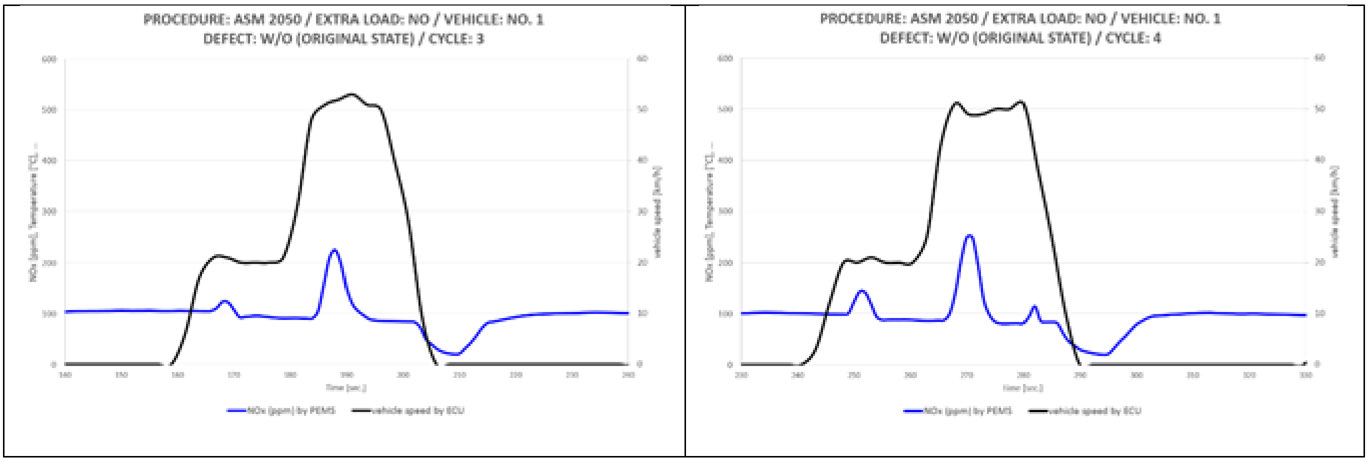


Figure 114: VEHICLE1 ASM2050, without defect

1.2 With defect (w defect)

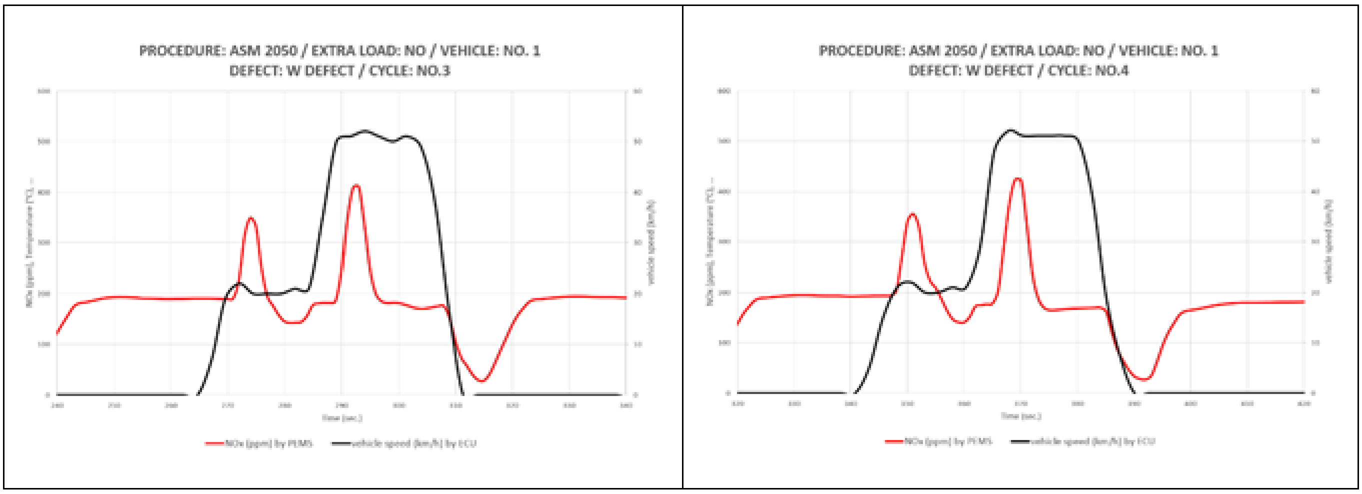


Figure 115: VEHICLE1 ASM2050, with defect

1.3 Direct comparison with/without defect

This measurings (with/without defect) of cause was performed at different dates and times, so the measurings are not directly comperable. But the cycle is well defined, it was always the same driver and shown is for both cases always the same cycle (3, 4, 5,…). With this illustration you can see the different levels for NOx very clear.

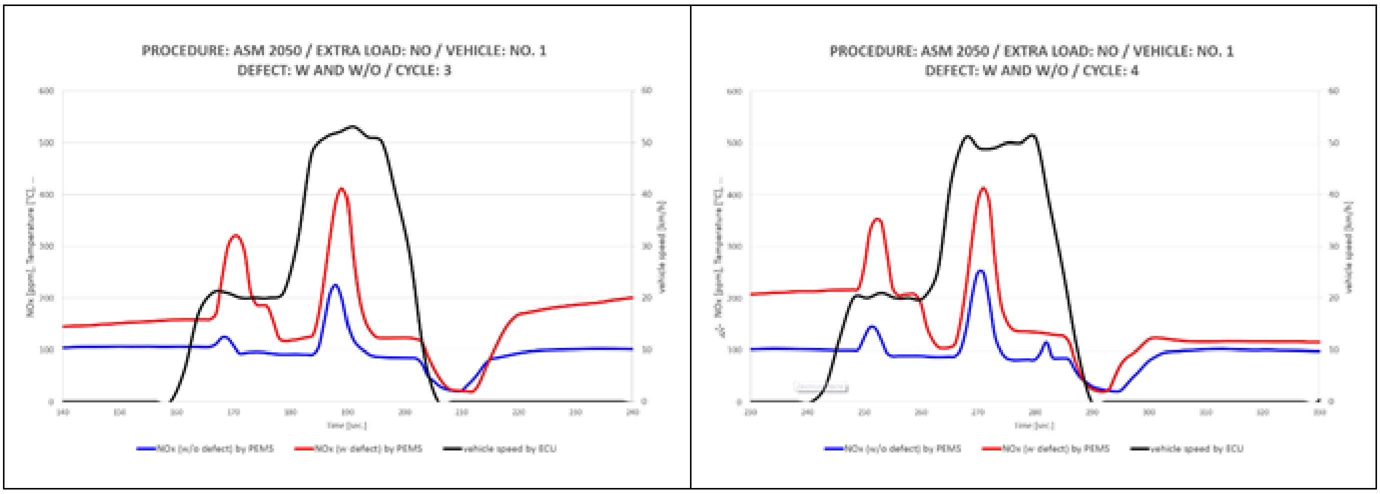


Figure 116: VEHICLE1 ASM2050, comparison with & without defect

→ significant higher level of NOx with defect.

1.4 Total and mean values, vehicle 1, ASM 2050

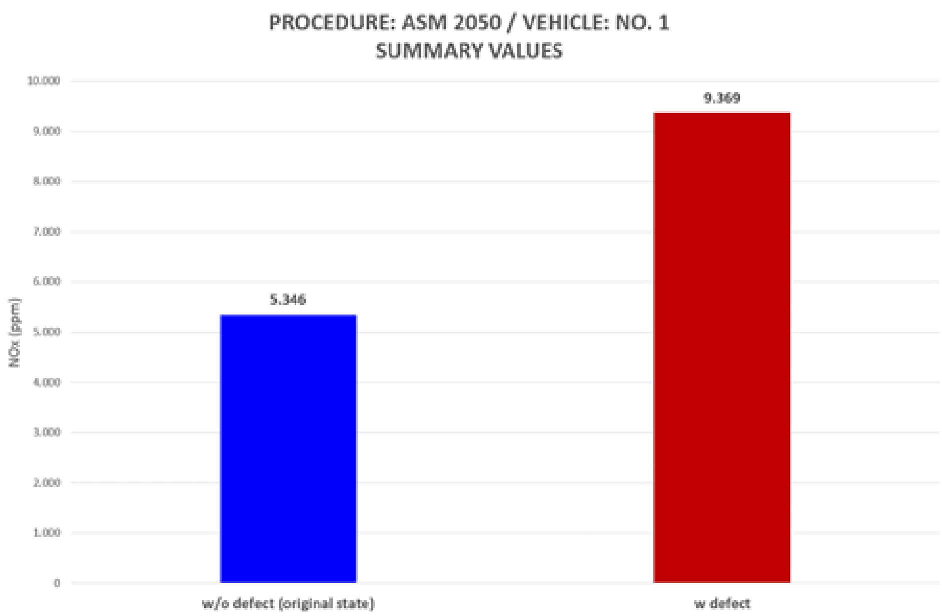


Figure 117: VEHICLE1 ASM2050, summary values

Total ppm over the ASM2050-cycles (always mean of 5 cycles)

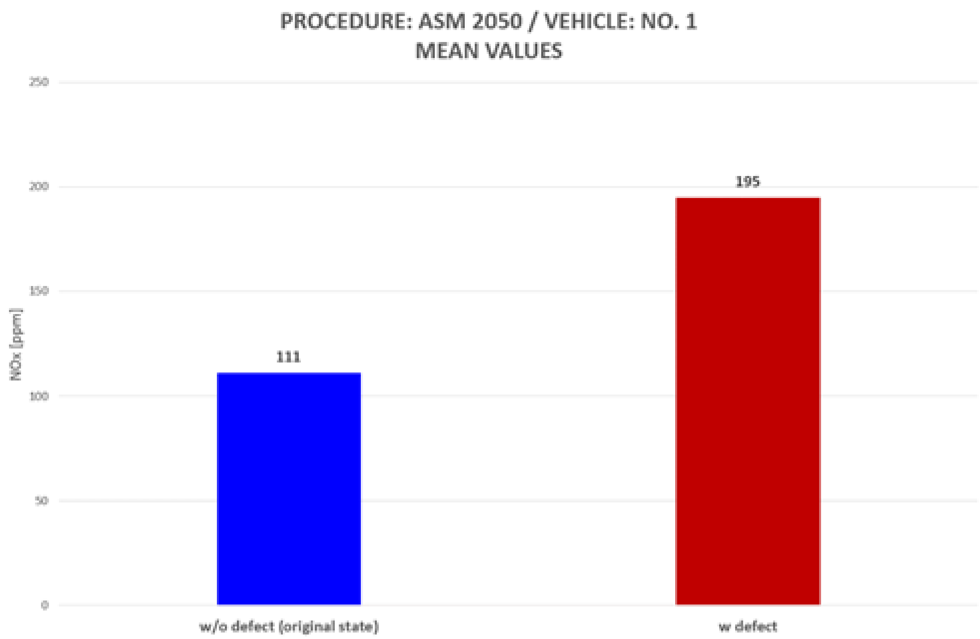


Figure 118: VEHICLE1 ASM2050, Mean values

Mean values of the ASM2050-cycles (always mean of 5 cycles)

1.5 Ratios with/without defect:

The table/ratios are relevant for the total values as well as for the mean values (see graphs above)

Ratio n.i.o./i.o.	**1,8**

Table 46: VEHICLE1 ASM2050, Ratio with and without defect

2. Further Investigations

2.1 NOx sensor "on board"

Vehicle 1 is equipped with an SCR-system and for this also with an NOx sensor "on board" to control the NOx emissions after the SCR system. Such sensors normally are working among the same principle like a (wide-band) Lambda probe, but are calibrated to NOx.

In this case the signal of the on-board NOx sensor is available by the ECU via a diagnostic scantool (not within the standardized OBD !).

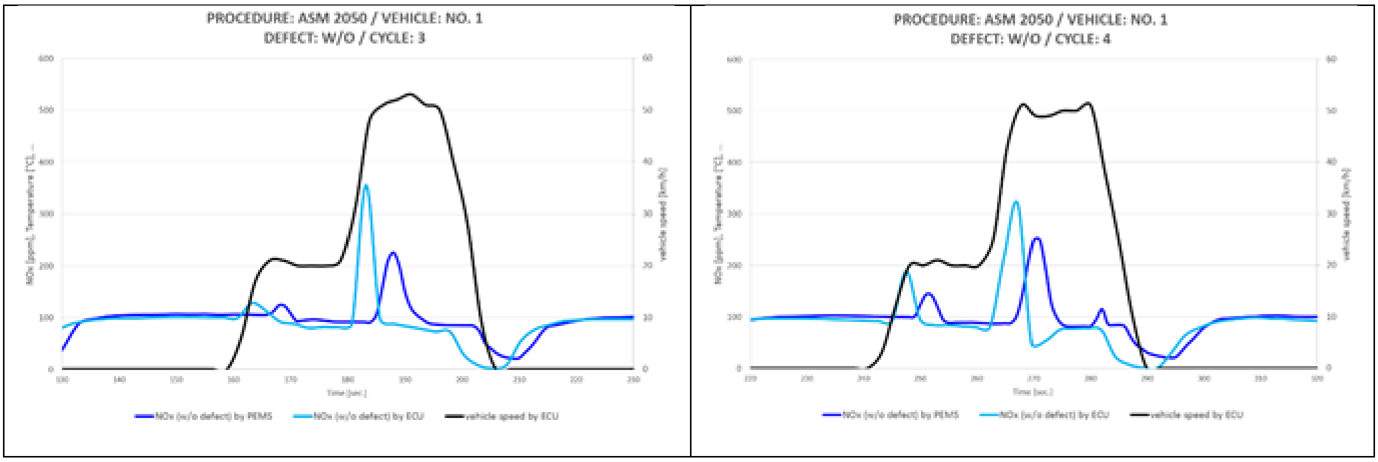


Figure 119: VEHICLE1 ASM2050, further investigation NO_X sensor

At the diagrams above we can see, that for idle speed and for stable conditions (diving constant) the NOx values of the on-board sensor and the (calibrated) PEMS measurement, which was used as “reference”, are amazing similar. For dynamic conditions (acceleration), the “peaks” are different. The NOx peaks of the ECU/onboard sensor are always higher than the measured values by PEMS.

2.2 Investigation of SCR:

A view to the exhaust temperature (available by the ECU) shows that the temperature is below 200 °C at idle speed, but above 200 °C while driving the ASM 2050 cycle.

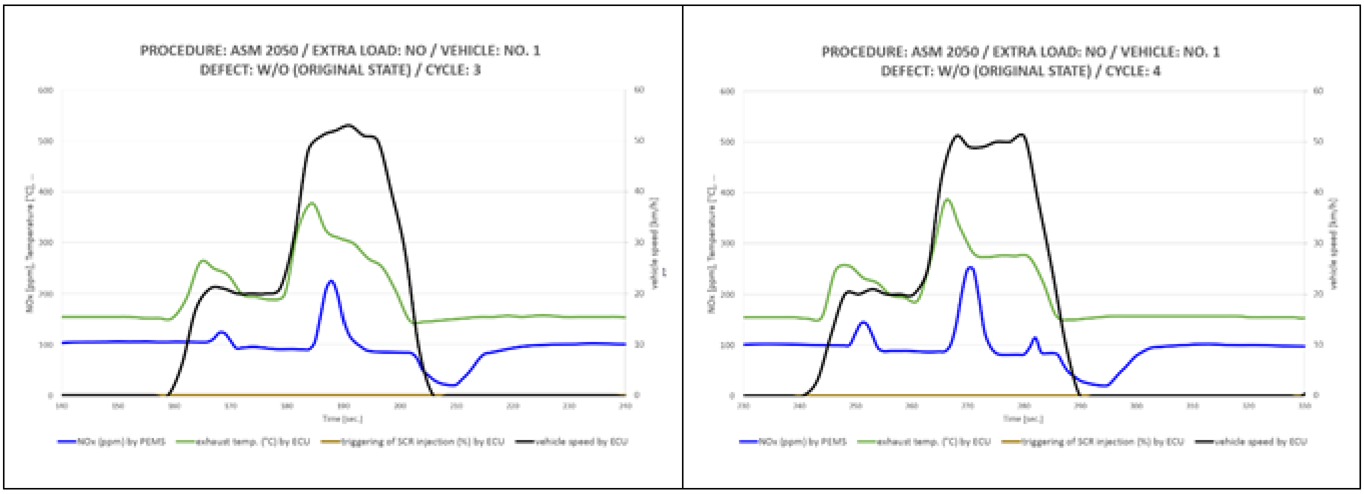


Figure 120: VEHICLE1 ASM2050, further investigation of SCR

In this case (vehicle 1) we can readout of the ECU also the triggering of the Urea injection (brown curve). Provided we can trust this readout, there is no injection and for this no SCR function.

This explains measured NOx in 1.2 (no effect by switch off SCR).

(Vehicle 1 is a VW and the investigations was done before the “software update” for dieselgate)

3. Problems with the specific vehicle:

non. Measurements was performed at an 4WD – Dyno, so all wheels are turning at the more or less same speed.

5.3.3.3. DT80

Procedure:	**DT80**	
Vehicle:	**No.1**	(VW Passat, DOC+DPF, SCR, Euro 6a)
Measurement:	**PEMS, ECU**	
Version:	1 / 2018.02.01	

1. Comparison: with/without defect

we measured
- original state (without defect)
- SCR-defect (mechanical damaged)

shown is always cycle 2 of 3 driven cycles

a. Without defect (original state)

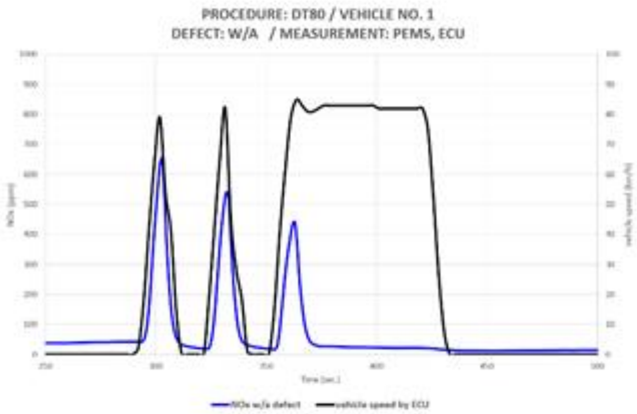


Figure 121: VEHICLE1 DT80, without defect

b. **With defect**

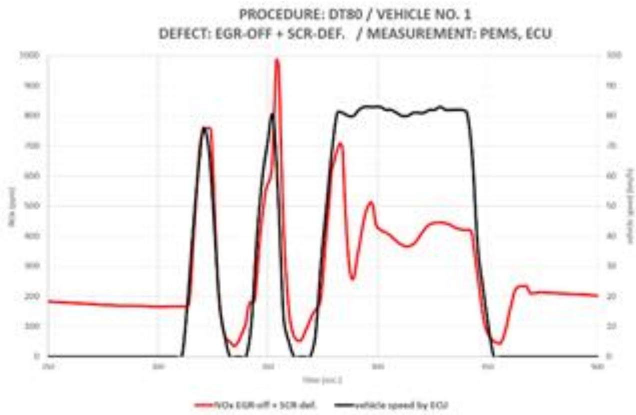


Figure 122: VEHICLE1 DT80, with defect

c. Direct comparison with/without defect

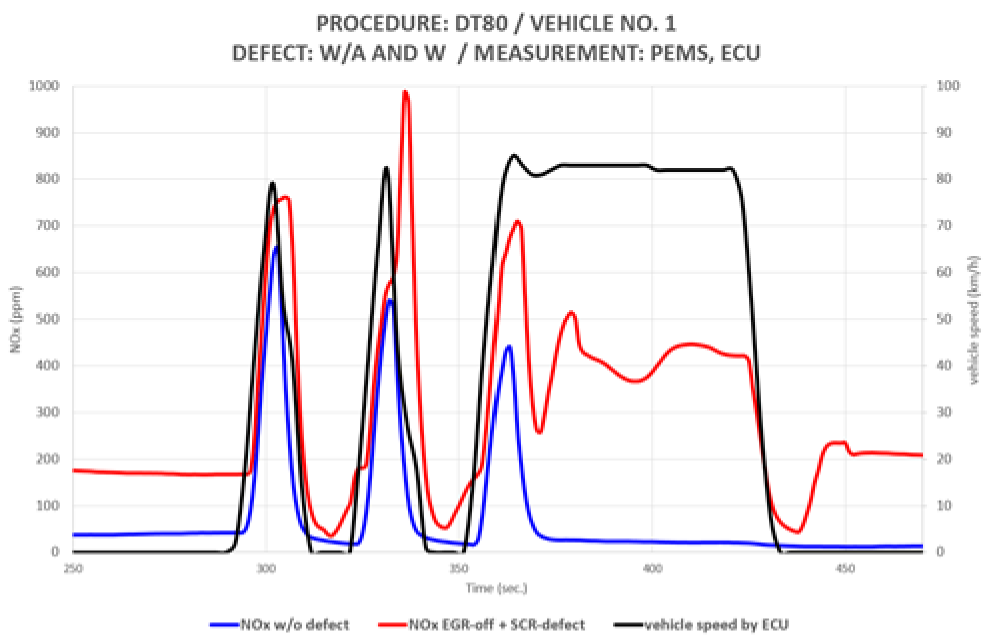


Figure 123: VEHICLE1 DT80, direct comparison with and without defect

1.4 Total and mean values, vehicle 1, DT80 cycle

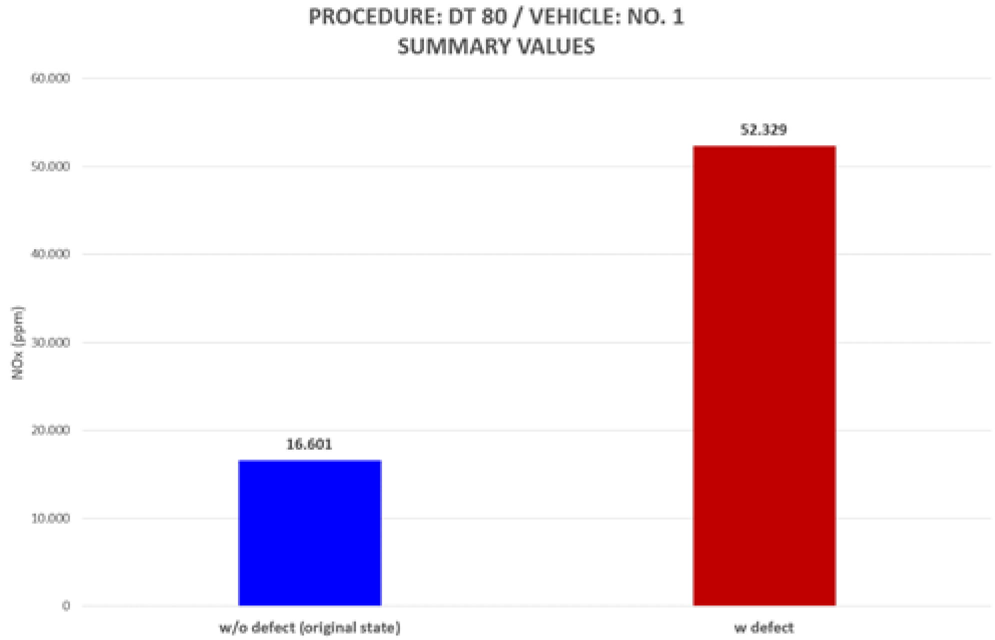


Figure 124: VEHICLE1 DT80, summary values

Total values (mean of 3 DT80-cycles)

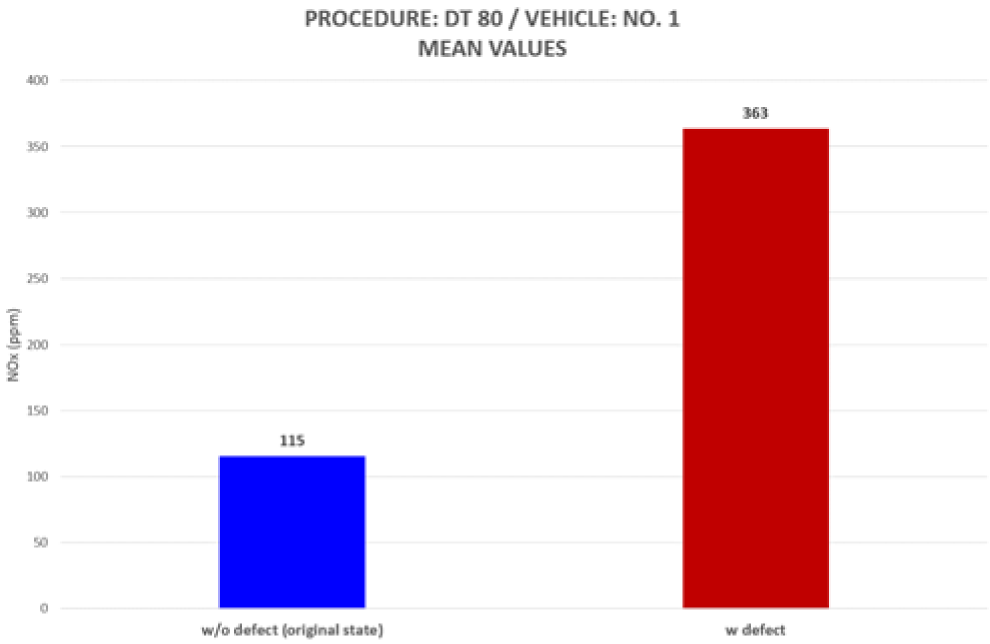


Figure 125: VEHICLE1 DT80, mean values

Mean values of the DT80-cycles (mean of 3 cycles)

1.5 Ratio with/without defect:

The ratio is relevant for the total values as well as for the mean values (see graphs in 1.4)

Ratio n.i.o./i.o.	**3,2**

Table 47: VEHICLE1 DT80, Ratio with and without defect

→ high ratio (w/o defect – w defect)
→ very good results, but DT80-cycle needs a relative long time and is very "noisy"
→ so the effort is relatively high

2. Further Investigations

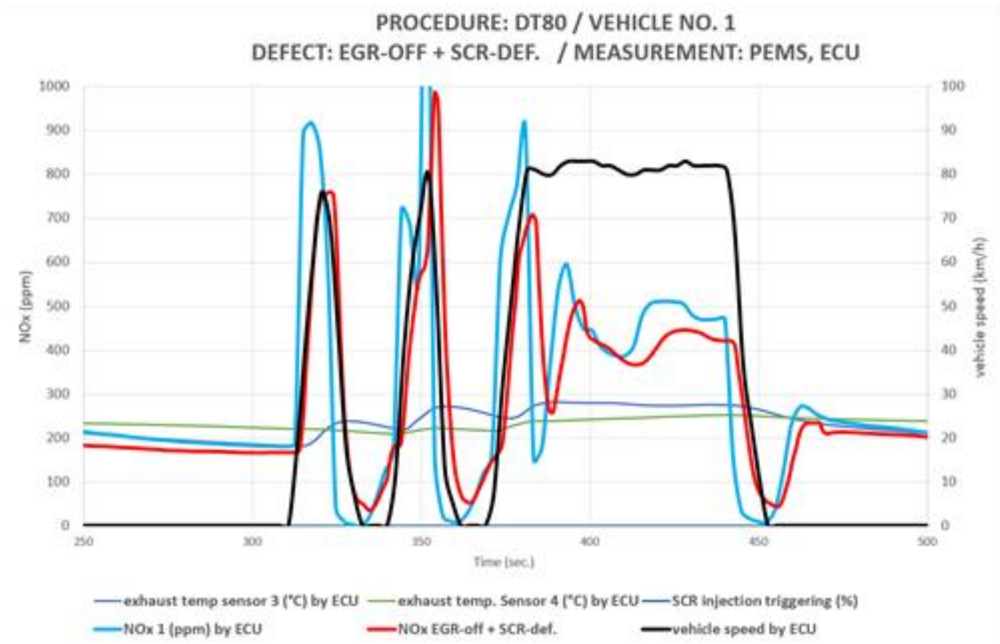


Figure 126: VEHICLE1 DT80, further investigation

→ relatively good correlation of the "on-board sensor" (NOx) with the PEMS measurement. The on-board sensor is in general higher.
→ exhaust temperature for the DT80-cycle is above 200 °C (depending on the place of temp. sensor)
→ SCR/Urea injection is very low (mostly nothing)

Problems with the specific vehicle:

No technical problem accrued

5.3.3.4. AVL Cycle

Procedure:	**AVL method**	
Vehicle:	**No.1**	(VW Passat, DOC+DPF, SCR, Euro 6a)
Measurement:	**PEMS, ECU**	
Version:	1 / 2018.03.01	

3. Comparison: with/without defect

we measured
- original state (without defect)
- SCR-defect (mechanical damaged)

a. Without defect (original state) some examples of course

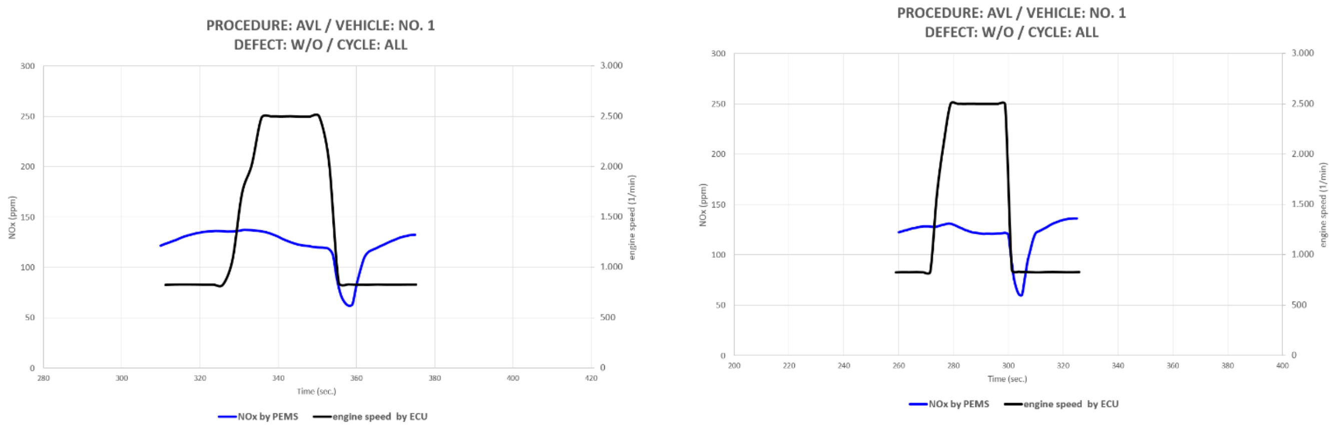


Figure 127: VEHICLE1 AVL cycle, without defect

b. With defect some examples of course

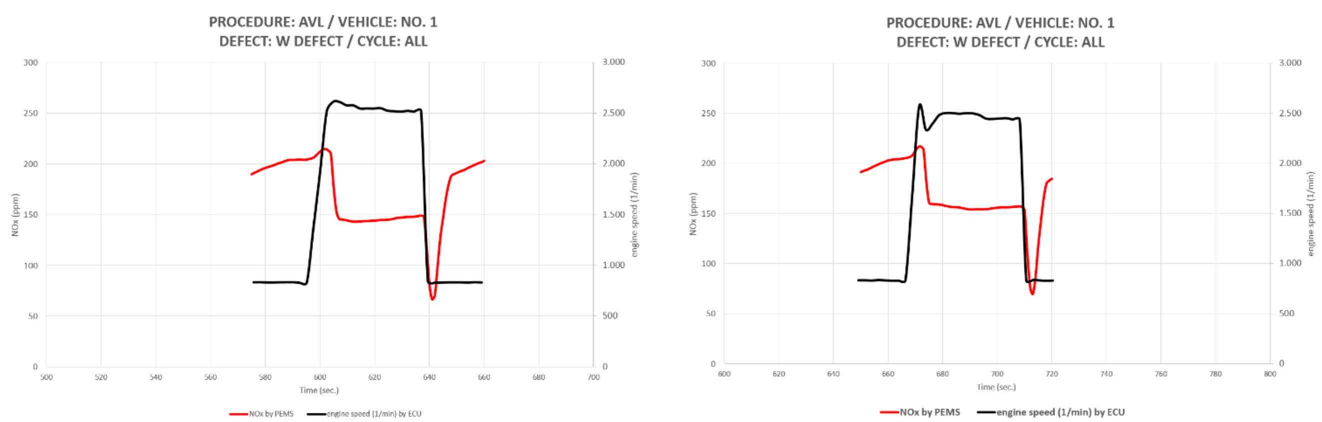


Figure 128: VEHICLE1 AVL cycle, with defect

c. Without defect (original state) overview : NOx peaks

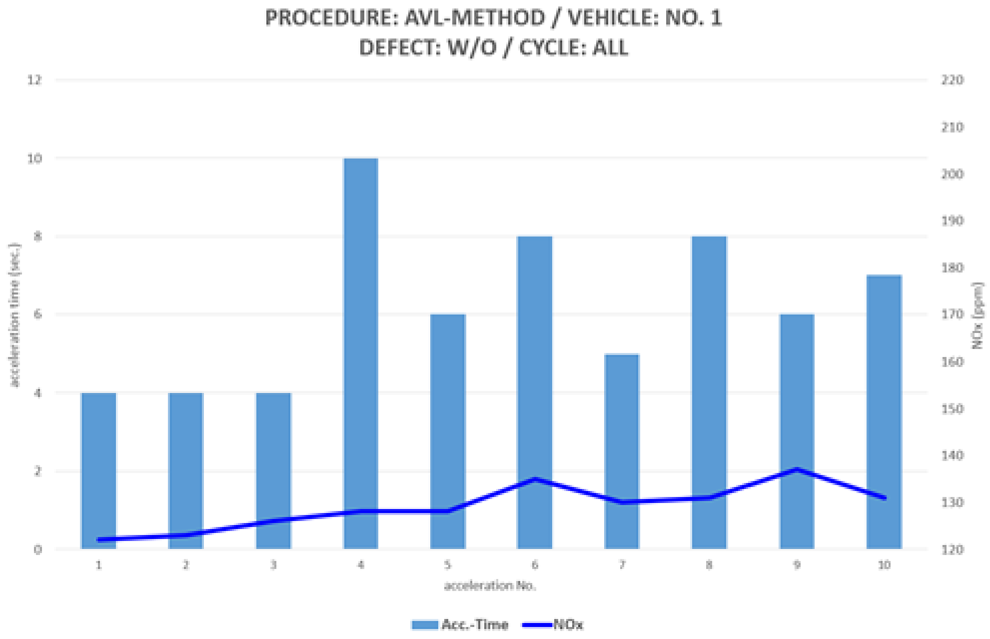


Figure 129: VEHICLE1 AVL cycle, without defect overview

1.4 With defect overview NOx peaks

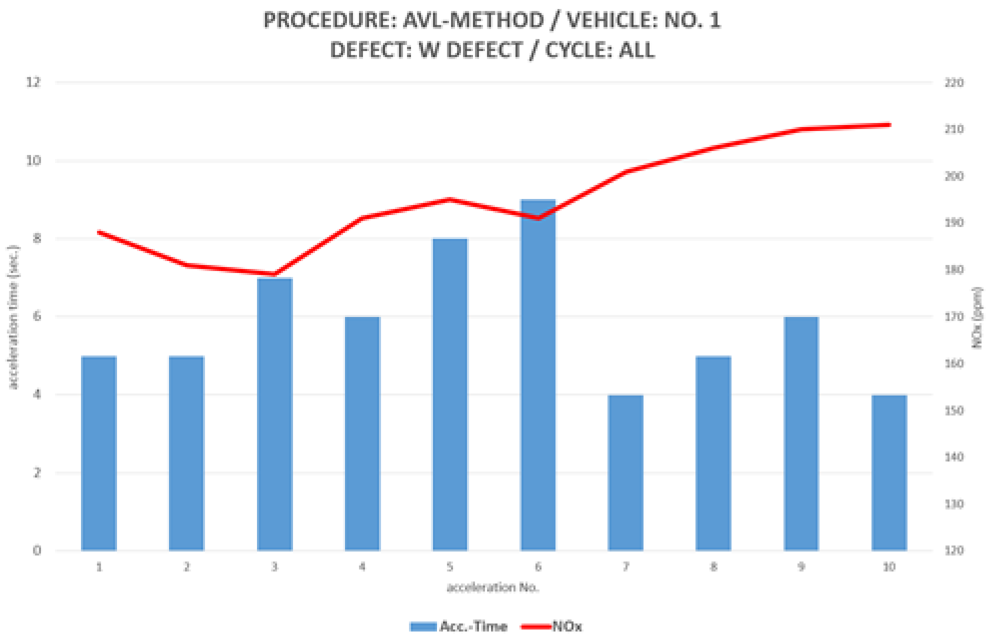


Figure 130: VEHICLE1 AVL cycle, with defect overview

→ dependence acceleration time/NOx. Short acceleration time means high NOx peaks/long acceleration time means low NOx peaks

→ measurings without defect: variance of NOx is inside accuracy of measuring (PEMS)
→ higher values with defect

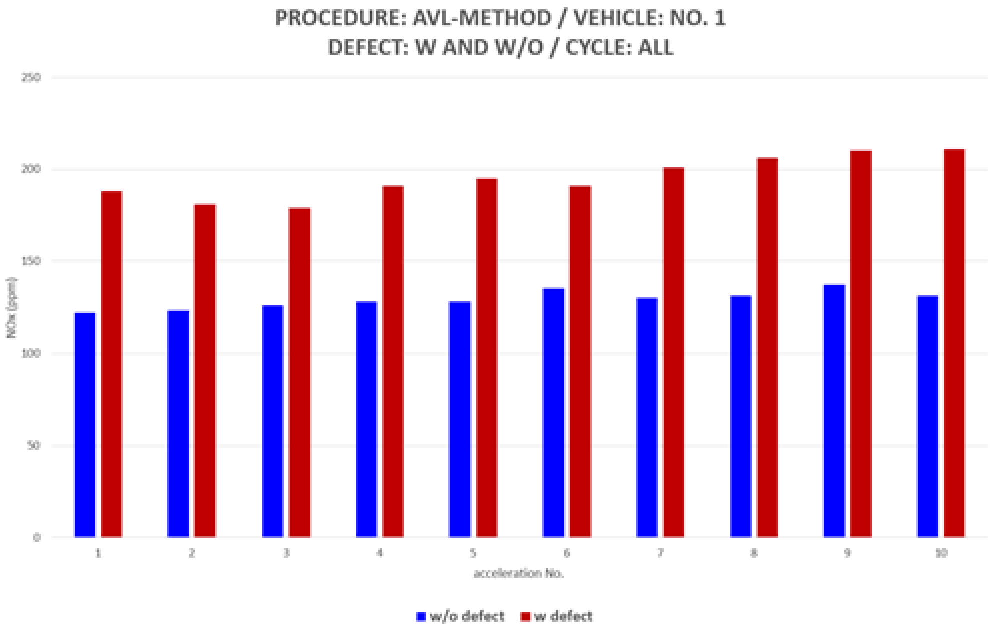


Figure 131: VEHICLE1 AVL cycle, with and without defect

1.5 Ratios with/without defect:

Ratio n.i.o./i.o.	**1,5**

Table 48: VEHICLE1 AVL cycle, Ratio with and without defect

4. Further Investigations

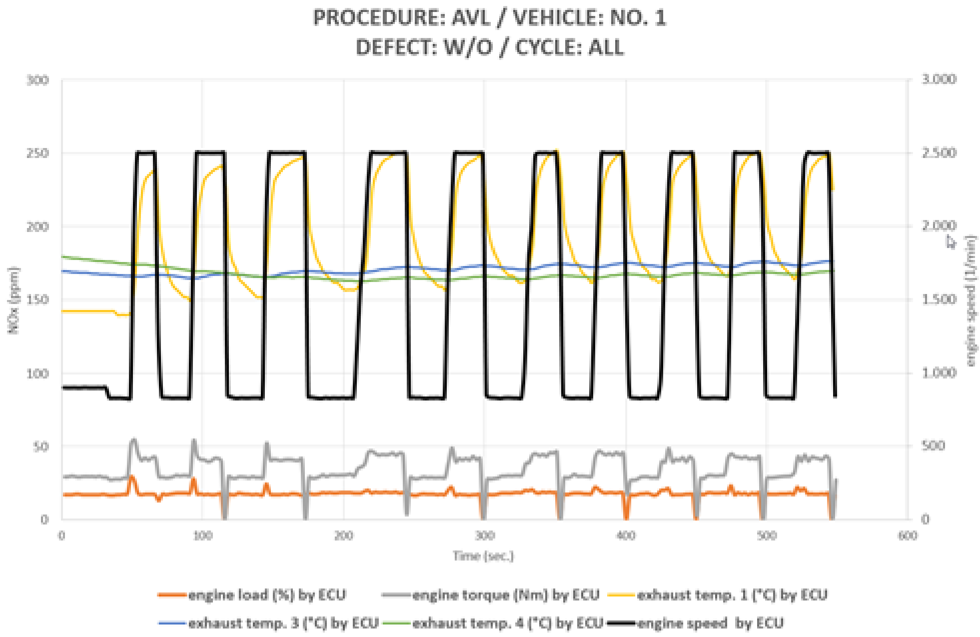


Figure 132: VEHICLE1 AVL cycle, further investigation

→ engine load (by ECU) and torque are not very high at AVL-Method
→ exhaust temperature is not very high at AVL-Method (< 200 °C)

Problems with the specific vehicle:

No.

5.3.4. Lab tests Vehicle 2

5.3.4.1. Installed failure

Vehicle No. 2 is a vehicle with Euro 5. It is not equipped with a SCR-system. The only NOx aftertreatment system is the EGR-system.

The installed failure for this vehicle was to manipulate the EGR-system, by reducing the exhaust tube to the air intake with a simple plate out of metal and with a bore in the middle.

The OBD-System didn't notice this failure over all the time of testing (about 100 km on dyno and on road, many engine starts,…). The indicator lamp (MIL) was off and no trouble code was stored

Figure 133: VEHICLE2, installed failure

5.3.4.2. ASM2050

Procedure:	**ASM2050**	(with different Load)
Vehicle:	**No.2**	(Polo, EGR, Oxi-Cat + DPF, Euro 5a)
Measurement:	**PEMS**	
Version:	1 / 2018.29.01	

Comparison: with/without defect

Driving cycles with different load, record of NOx :

a. Without defect (original condition)

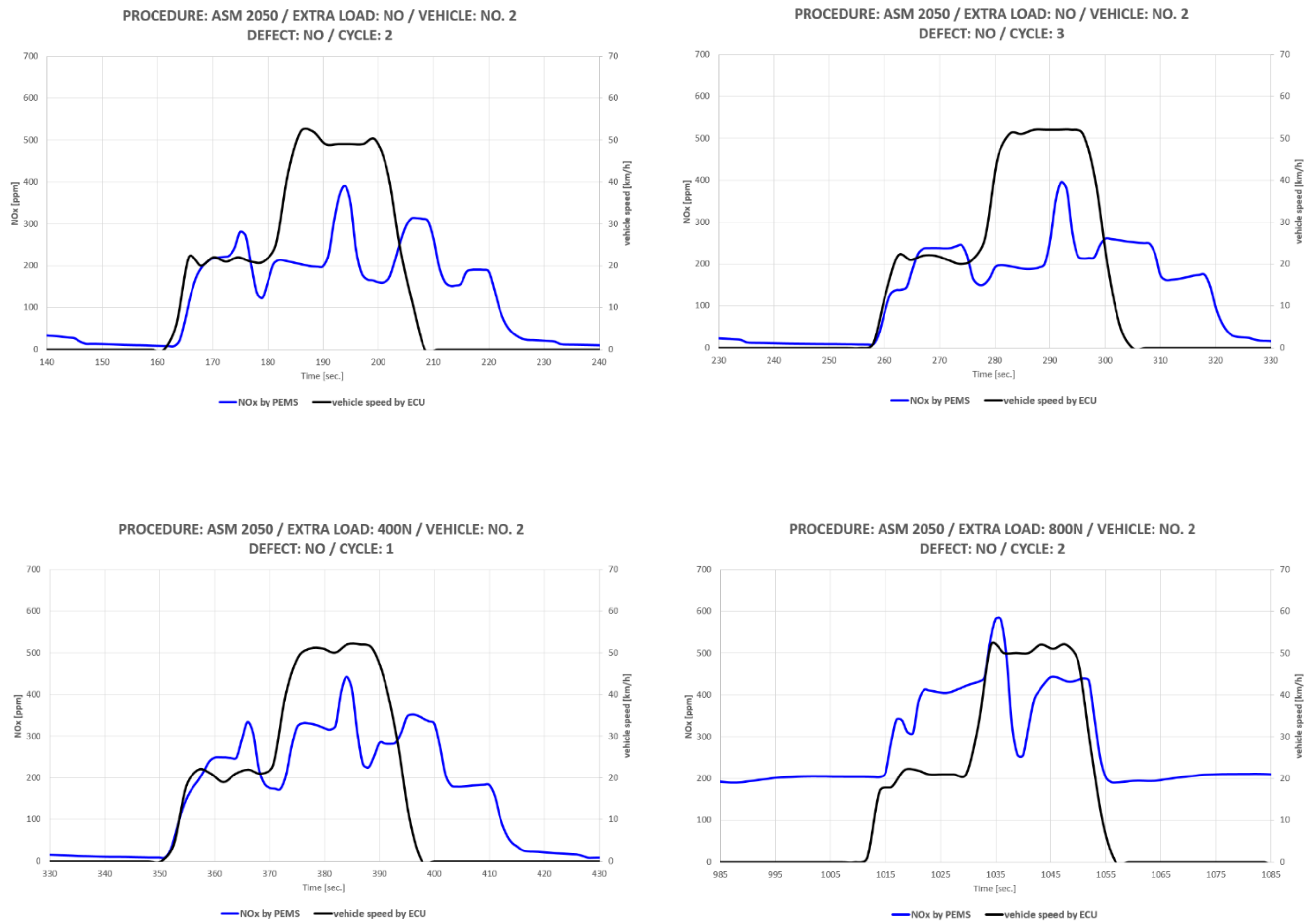


Figure 134: VEHICLE2 ASM2050, without defect

b. With defect

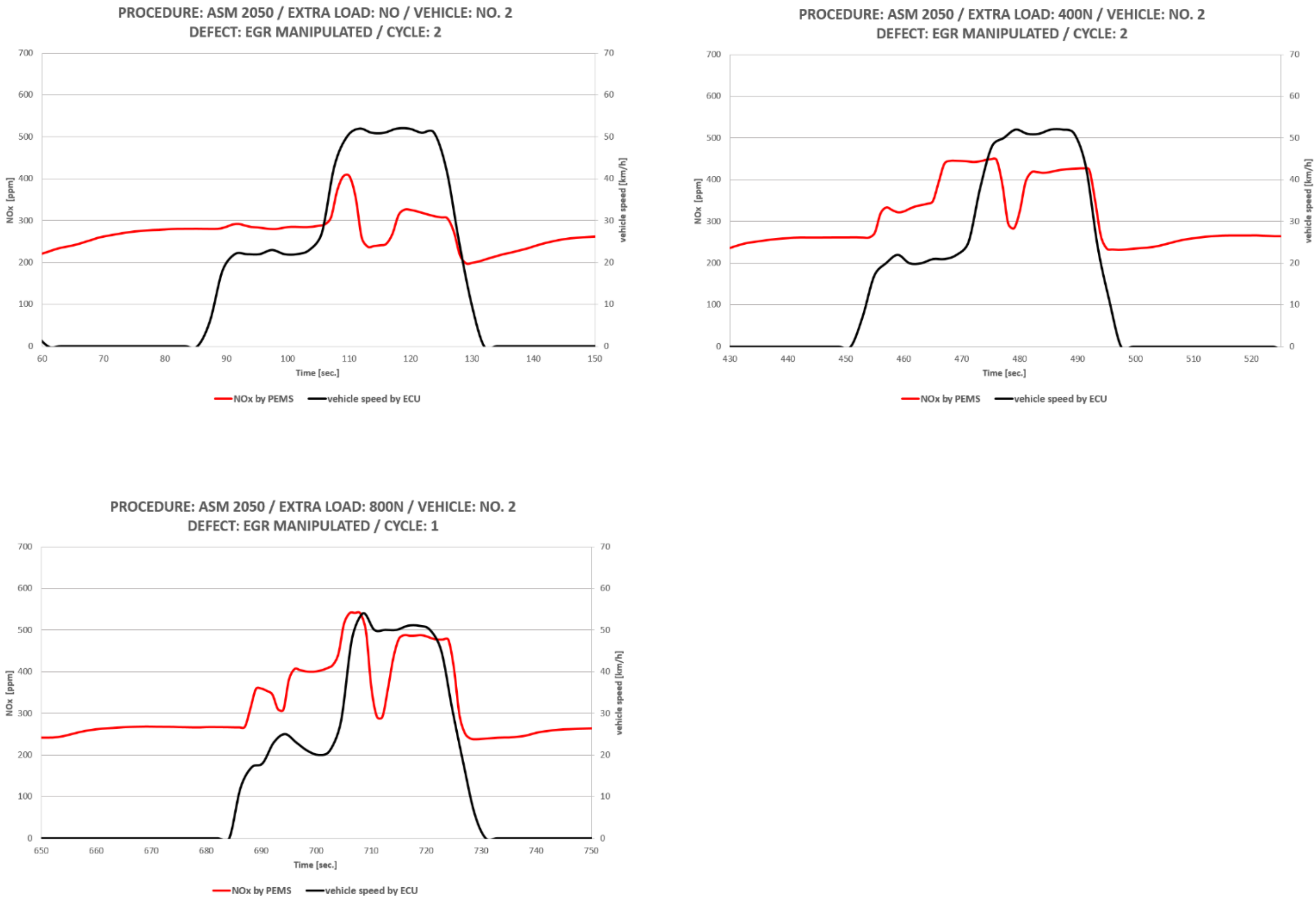


Figure 135: VEHICLE2 ASM2050, with defect

→ vehicle 2 is a Euro 5 vehicle. It is equipped (only) with an EGR-System to reduce NOx (no SCR or LNT)
→ the level of NOx is all in all much higher than the Euro-6-vehicles
→ higher NOx-Values with higher load. At original conditions (without defect) as well as with defect.

For Euro-6-vehicles and original conditions (without defect) we can see no (!) dependence of NO_X from the vehicle load. That means an SCR-System reduces NOx very good, provided that it works well
→ NOx measurement by PEMS is very sensible (see waveforms above). We can see little corrections of the accelerator pedal at the NOx-values.
→ Triggering of values for a PEMS is 1 Hz (1 value per second). This is enough for a real RDE measuring over a long time/distance (about 1,5 hour). For a short test period like ASM2050 we need a higher triggering rate (proposal 5 Hz) for having a better measurement.

c. Direct comparison with/without defect

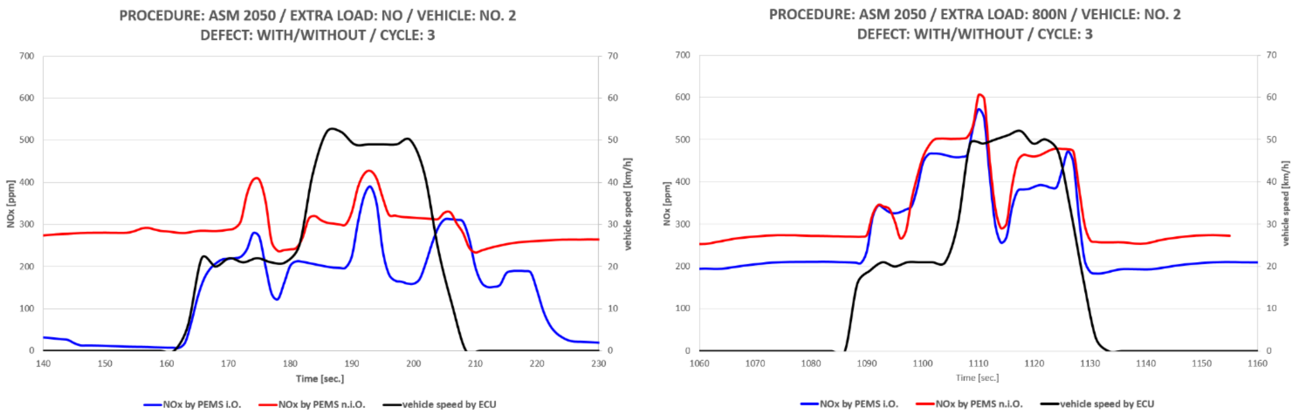


Figure 136: VEHICLE2 ASM2050, comparison with and without defect

→ see also the other vehicles. Difficult to compare, or better: not valid.
Same vehicle, same cycle, same driver, but off cause not done in parallel

1.4 Total and mean values, vehicle 2, ASM 2050

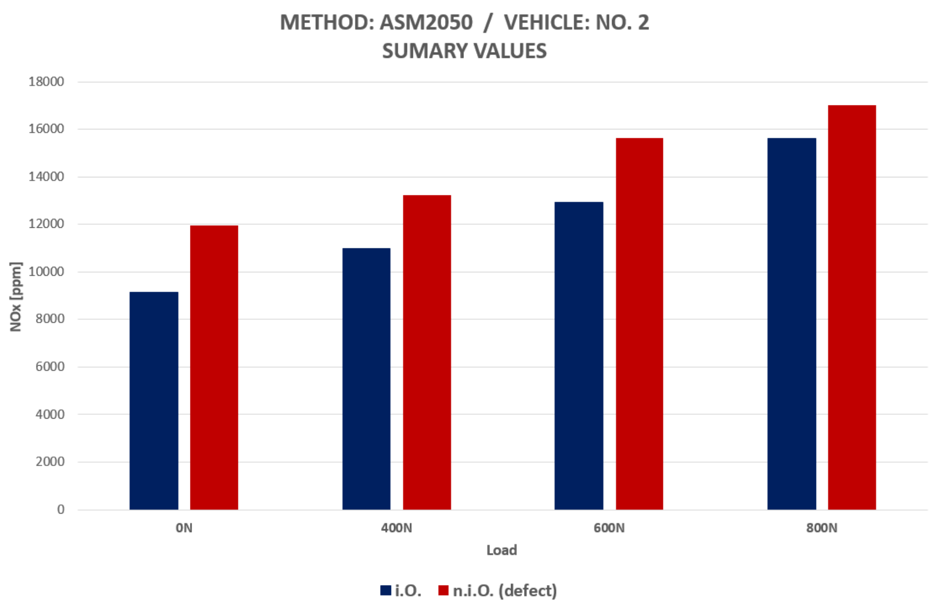


Figure 137: VEHICLE2 ASM2050, sumary values

Total ppm/sec. over the ASM2050-cycles (always mean of 3 cycles)

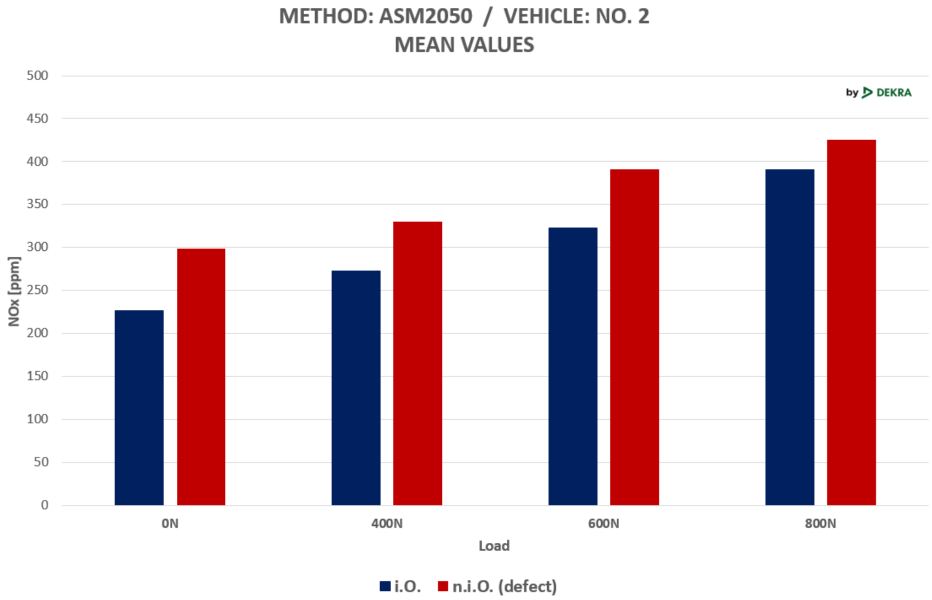


Figure 138: VEHICLE2 ASM2050, mean values

Mean values of the ASM2050-cycles (always mean of 3 cycles)

1.5 Ratios with/without defect:

The table/ratios are relevant for the total values as well as for the mean values (see graphs in 1.4)

	0 N	400 N	600 N	800 N
Ratio n.i.o./i.o.	**1,3**	**1,2**	**1,2**	**1,1**

Table 49: VEHICLE2 ASM2050, ratio with and without defect

→ ratio (n.i.O./i.O.) is not as clearly as at the more modern vehicles (Euro 6)
→ compared to the more modern vehicles (Euro 6), the level of NOx is very high especially in i.O.-condition 3-4x

5. Further Investigations

No.

Problems with the specific vehicle:

No.

5.3.4.3. DT80

Comparison: with/without defect

Some examples for driving cycles with different load, record of NOx :

Without defect (original condition)

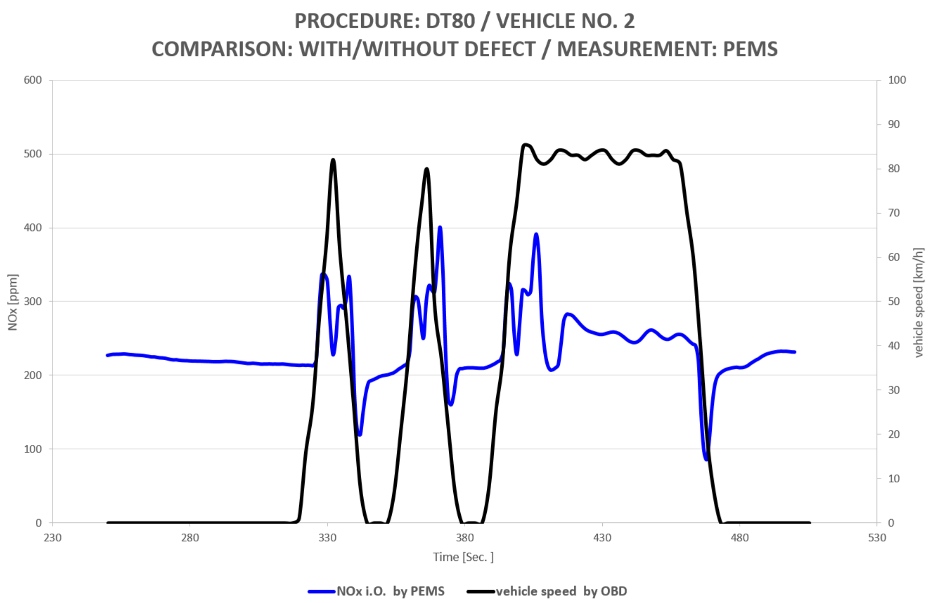


Figure 139: VEHICLE2 DT80, without defect

With defect

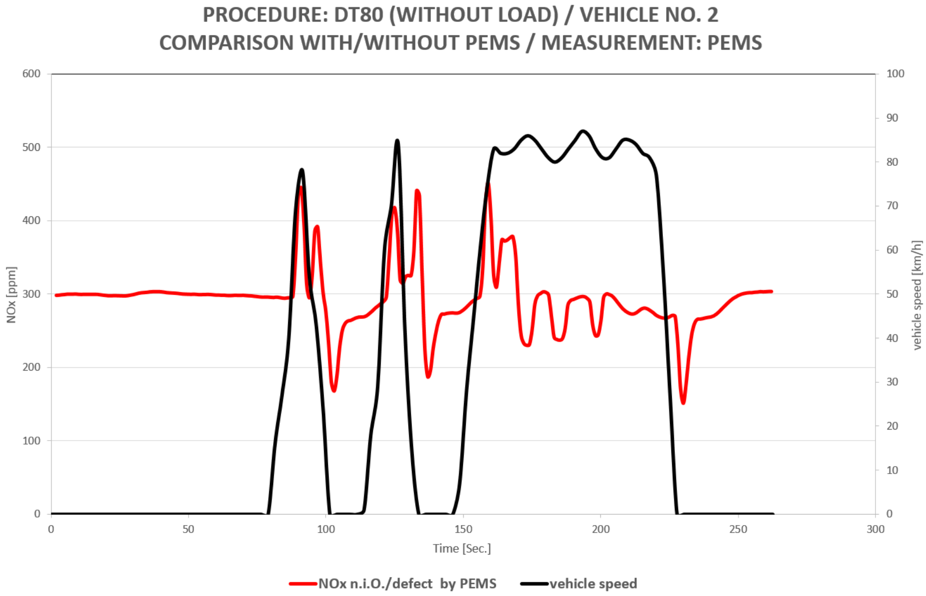


Figure 140: VEHICLE2 DT80, with defect

Direct comparison with/without defect

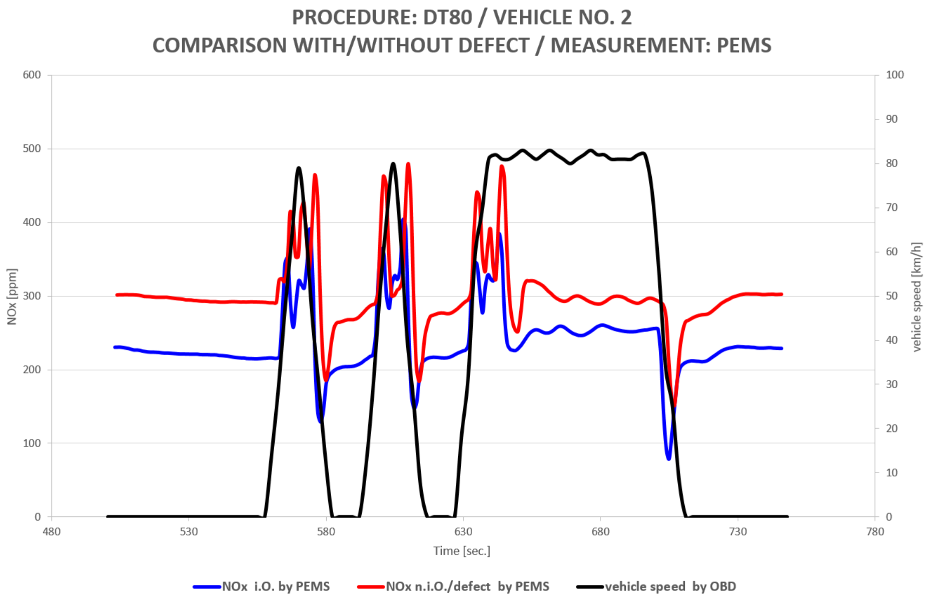


Figure 141: VEHICLE2 DT80, comparison with and without defect

Total and mean values, vehicle 2, DT80 cycle

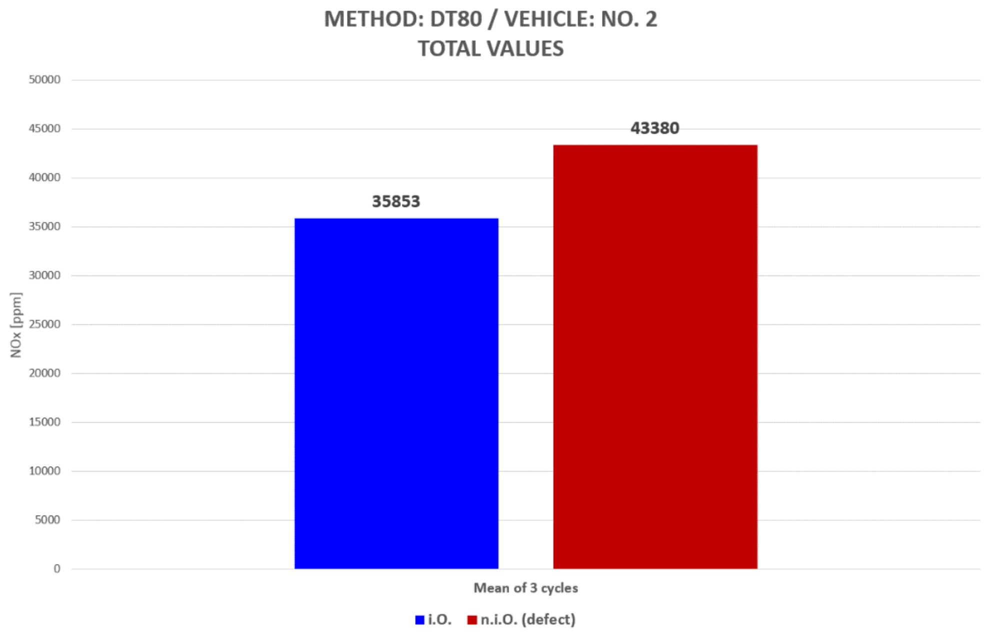


Figure 142: VEHICLE2 DT80, total value

Total values (mean of 3 DT80-cycles)

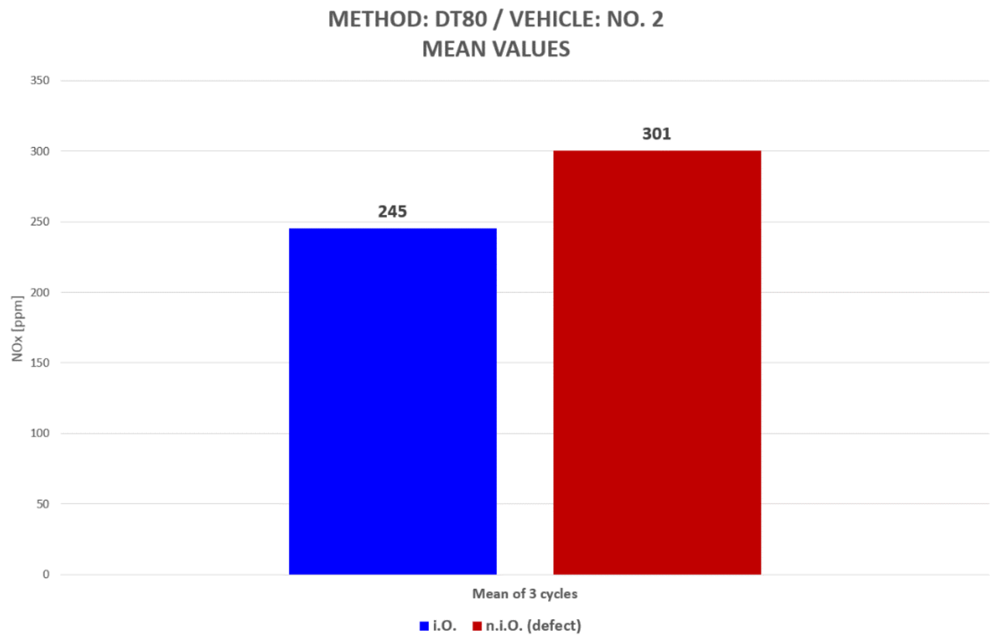


Figure 143: VEHICLE2 DT80, mean value

Mean values of the DT80-cycles (mean of 3 cycles)

Ratios with/without defect:

The table/ratios are relevant for the total values as well as for the mean values (see graphs in 1.4)

Ratio n.i.o./i.o.	**1,2**

Table 50: VEHICLE2 DT80, ratio with and without defect

→ ratio (n.i.O./i.O.) is not as clearly as at the more modern vehicles (Euro 6)
→ ratio (n.i.O./i.O.) is the same as for the ASM2050 cycle
(but ASM2050 cycle is faster, easier to drive and for this more effective)
→ compared to the more modern vehicles (Euro 6), the level of NOx is very high
especially in i.O.-condition 3-4x
→ DT80 tests was performed without “extra load”.

Further Investigations

No.

Problems with the specific vehicle:

No.

5.3.4.4. Short Test Drive

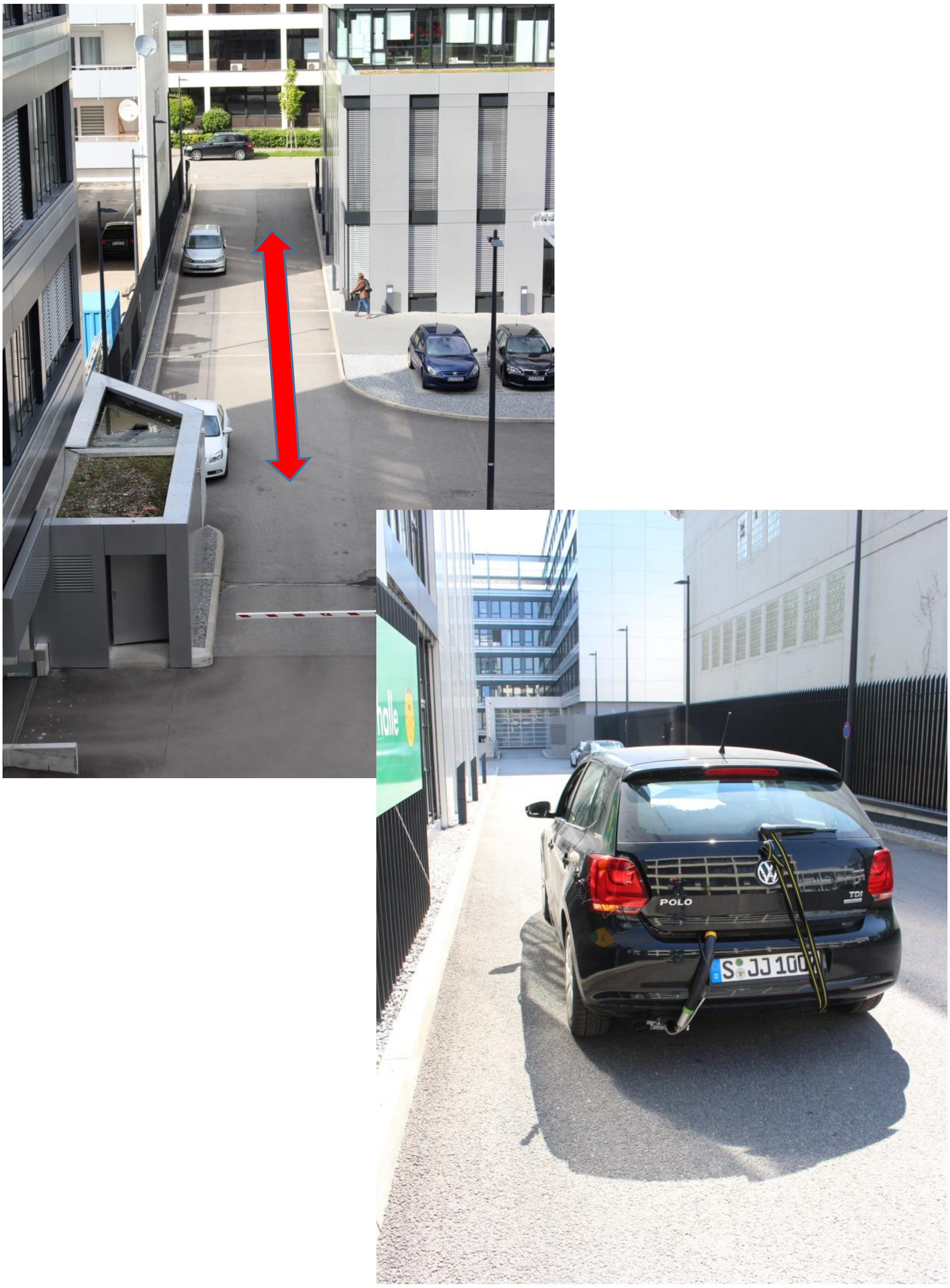
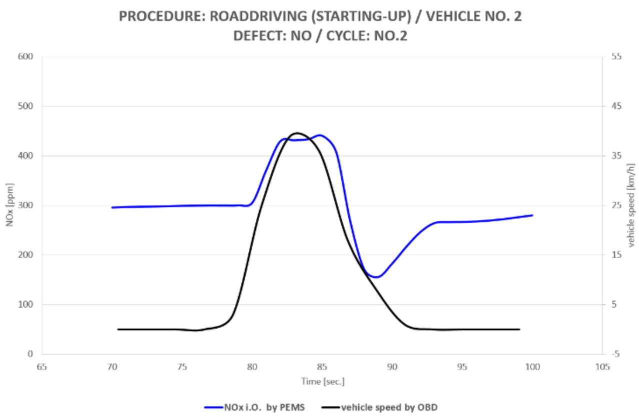


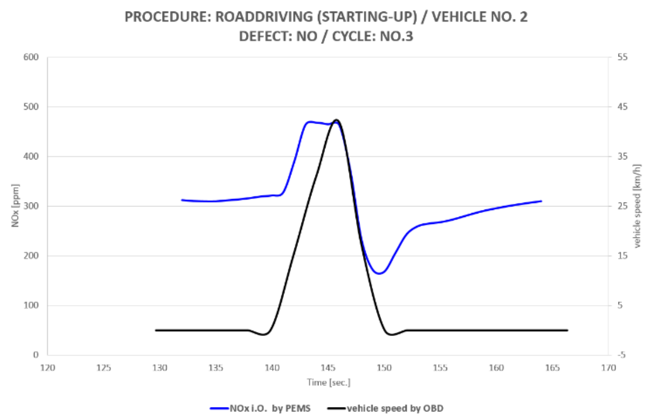
Figure 144: VEHICLE2 Short Test Drive

Comparison: with/without defect

Every “cycle” was a short rank (maneuver) for positioning the vehicle in the right direction/change the direction and after this an acceleration up to about 30 - 40 km/h (target).

Without defect





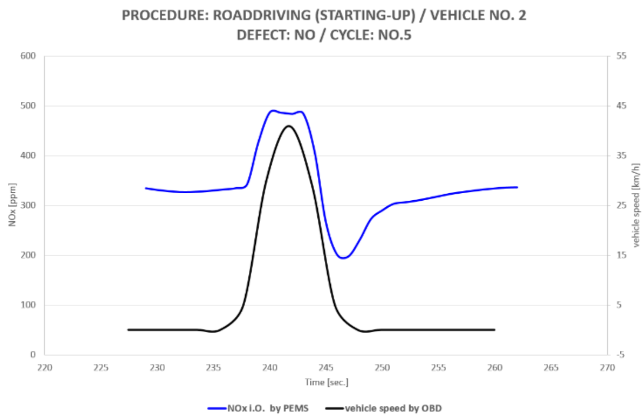
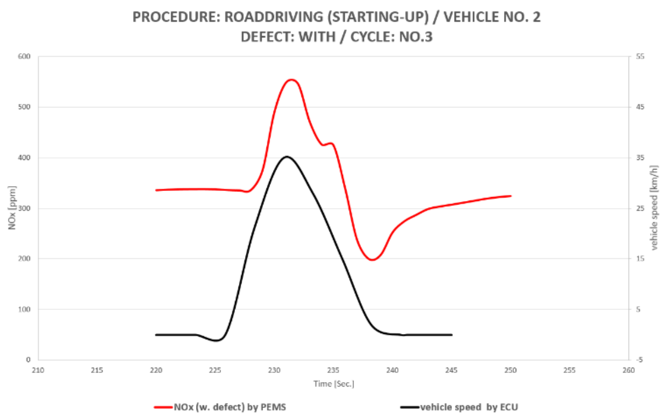


Figure 145: VEHICLE2 Short Test Drive, without defect

With defect, (see No. 4 installed failure)



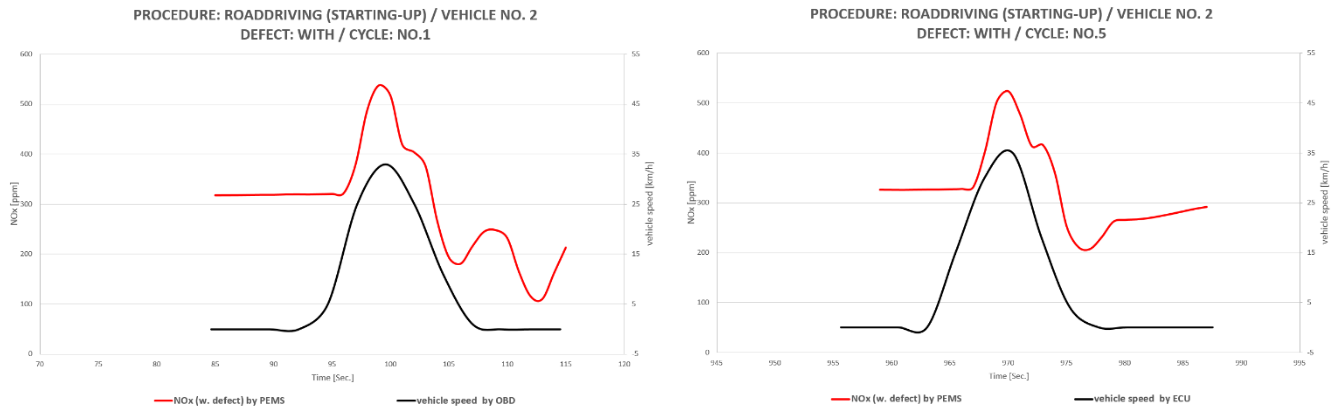


Figure 146: VEHICLE2 Short Test Drive, with defect

→ Reproducible higher level of NOx with defect, but not as strong as Euro 6 vehicles

Reflection of load

→ got some higher load for the tests "without defect" than "with defect". This might be one reason for having not so clear ratios (with defect/without defect).

→ for the tests the load and engine torgue was readout of the ECU of the vehicle. So both are calculated by the ECU and it is not clear how and what are the influences.

→ mean "load" out of 5 driving cycles was 93% for the i.O.-state (without defect) and 68% for the defect state.

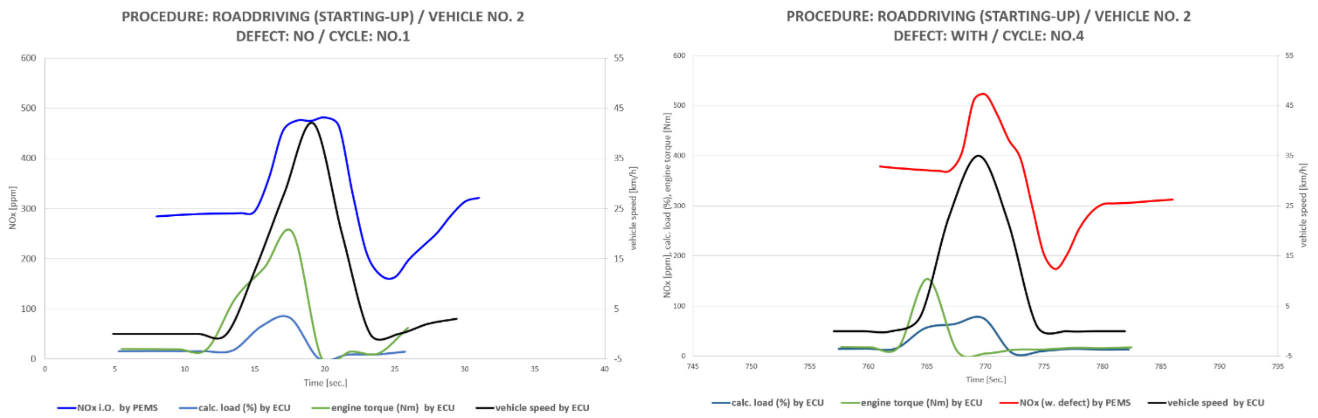


Figure 147: VEHICLE2 Short Test Drive, reflection of load

→ for the figures above there was selected cycles with comparable load (light blue, 76% and 81% of load). Again the effect of NOx (without defect/with defect) is not as clear as for Euro-6-vehicles, but the level of NOx all in all is much higher than for the Euro-6-vehicles.

→ For road tests the load and/or torque and the “curse” of speed/acceleration have to be well defined (like a little “cycle”).

Summary of the Roaddriving / start-up tests (vehicle 2):
(mean values of 5 cycles each (peaks))

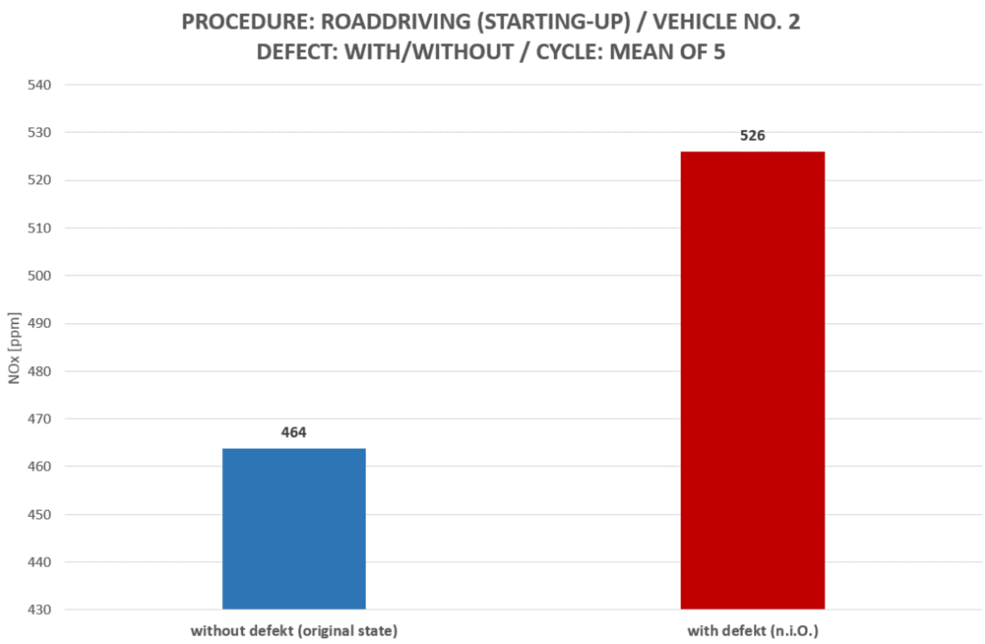


Figure 148: VEHICLE2 Short Test Drive, mean values

Ratio between vehicle i.o. and vehicle with defect:

	> 30 km/h
Ratio n.i.o./i.o.	**1,13**

Table 51: VEHICLE2 Short Test Drive, ratio with and without defect

→ comparable conditions are necessary
→ more investigations are necessary

Further Investigations

Engine load and exhaust temperature

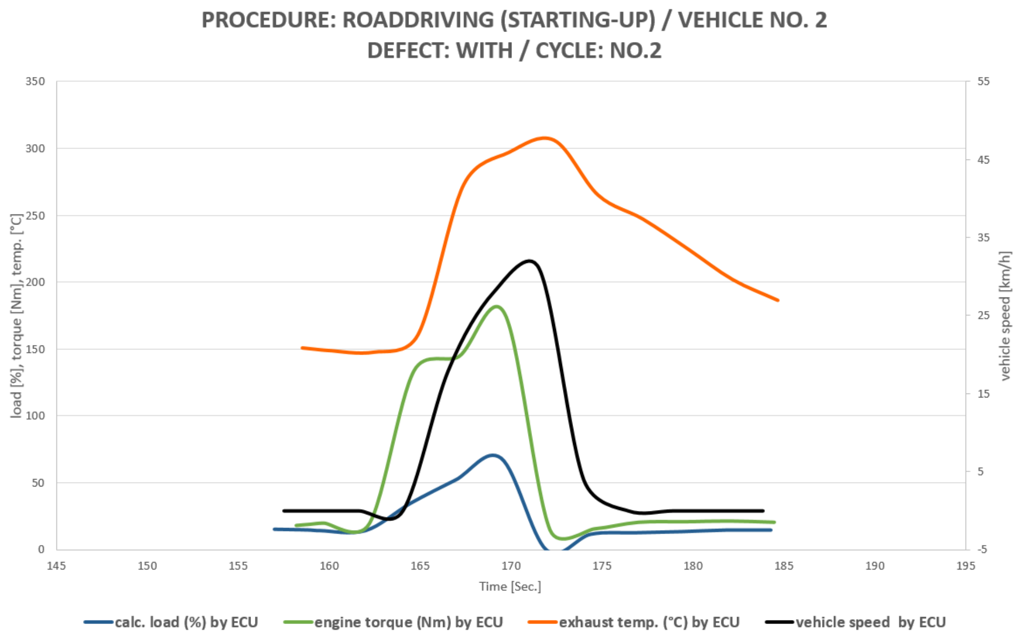


Figure 149: VEHICLE2 Short Test Drive, further investigation engine load and exhaust temperature

→ Engine load, torque and other informations are "often" available by the ECU
→ also the exhaust temperature
→ all this informations are <u>not</u> available within the standardized OBD!
→ the realization of this informations are not clear/standardized
(e.g. how is the "load" calculated, what influences. Place of temp. sensor, ….)
→ also not all informations are available in every case/vehicle
→ more "trustable" is the vehicle speed and this information is mostly always available
→ out of the vehicle speed the acceleration can easily be calculated.
→ see figures below

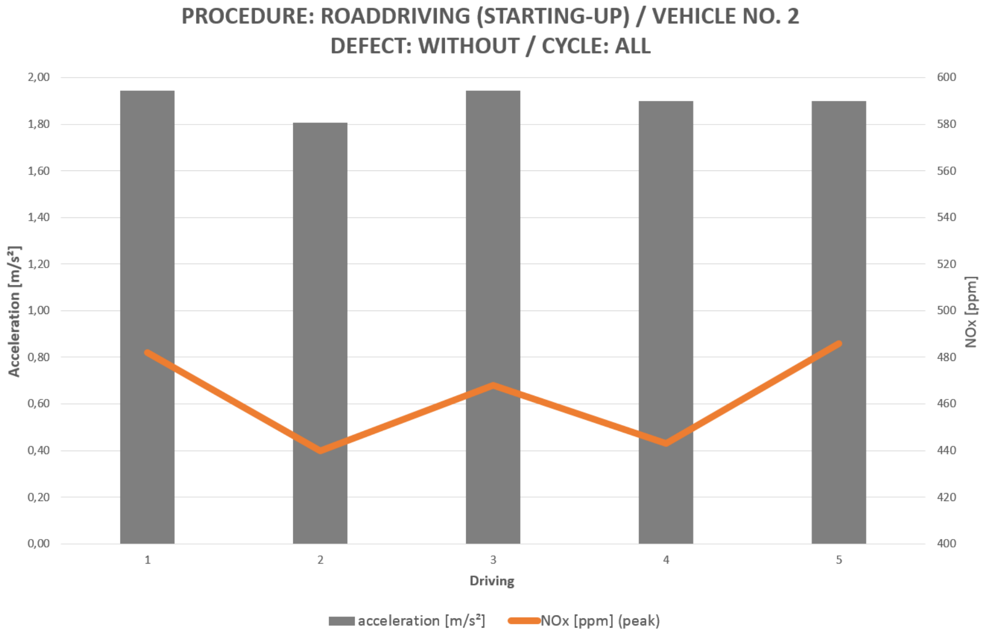


Figure 150: VEHICLE2 Short Test Drive, without defect, further investigation engine load and exhaust temperature

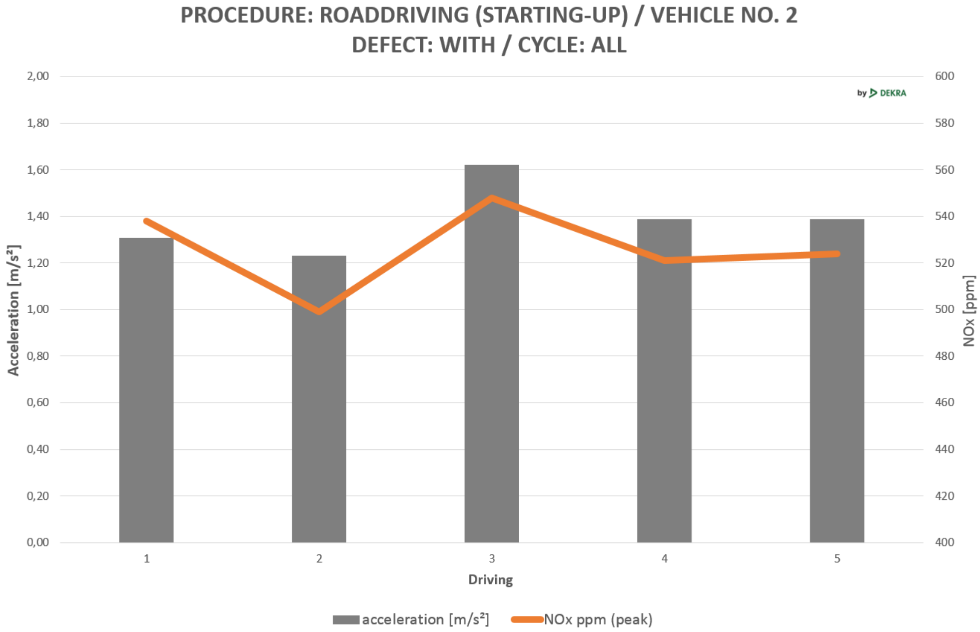


Figure 151: VEHICLE2 Short Test Drive, with defect, further investigation engine load and exhaust temperature

→ clearer results by using the acceleration (calculated out of the vehicle speed and the time).

→ The level of NOx follows the amount of the acceleration

Problems with the specific vehicle:

No.

5.3.5. Lab tests Vehicle 3

5.3.5.1. Installed failure

Vehicle No. 3 is a vehicle with Euro 6. It is not equipped with a SCR-system. The main NOx aftertreatment system is the EGR-system.

The installed failure for this vehicle was to manipulate the EGR-system, by reducing the exhaust tube to the air intake with a simple plate out of metal and with a bore in the middle.

The OBD-System didn't notice this failure over all the time of testing (about 100 km on dyno and on road, many engine starts,…). The indicator lamp (MIL) was off and no trouble code was stored.

Figure 152: VEHICLE3 Installed failure

5.3.5.2. ASM2050

Procedure:	**ASM2050**	(with different Load)
Vehicle:	**No.3**	(Kia Sportage 2,0 DTCi, Euro 6)
Measurement:	**PEMS**	
Version:	2 / 2017.05.18	

Comparison: with/without defect

Some examples for driving cycles with different load, record of NOx :

Significant higher level of NOx when vehicle has a defect (EGR). As well at high load as at low load.

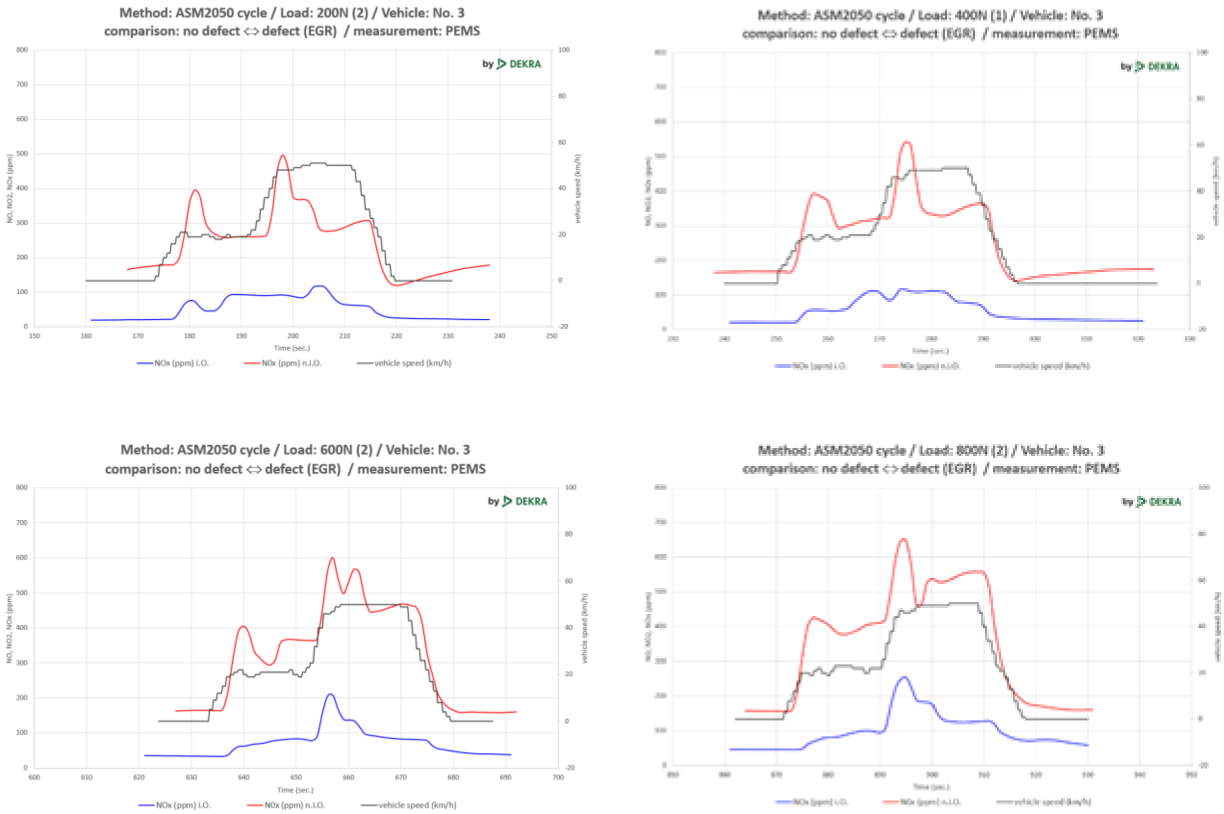


Figure 153: VEHICLE3 ASM2050, comparison with and without failure

Summary of the ASM2050 test (vehicle 3):
(mean values of 2 cycles each)

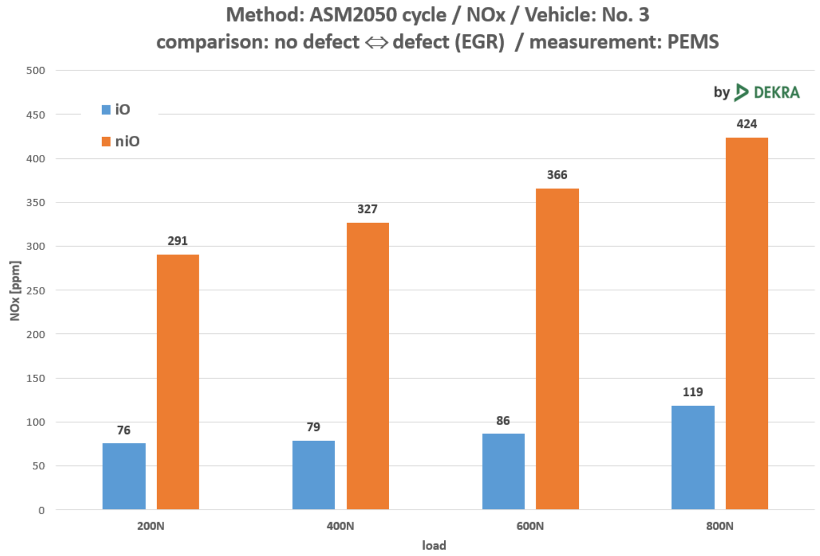


Figure 154: VEHICLE3 ASM2050, mean values with and without failure

Ratio between vehicle i.o. and vehicle with defect:

	200 N	400 N	600 N	800 N
Ratio n.i.o./i.o.	3,8	4,1	4,3	3,6

Table 52: VEHICLE3 ASM2050, ratio with and without failure

Further Investigations

Exhaust temperature depending on load

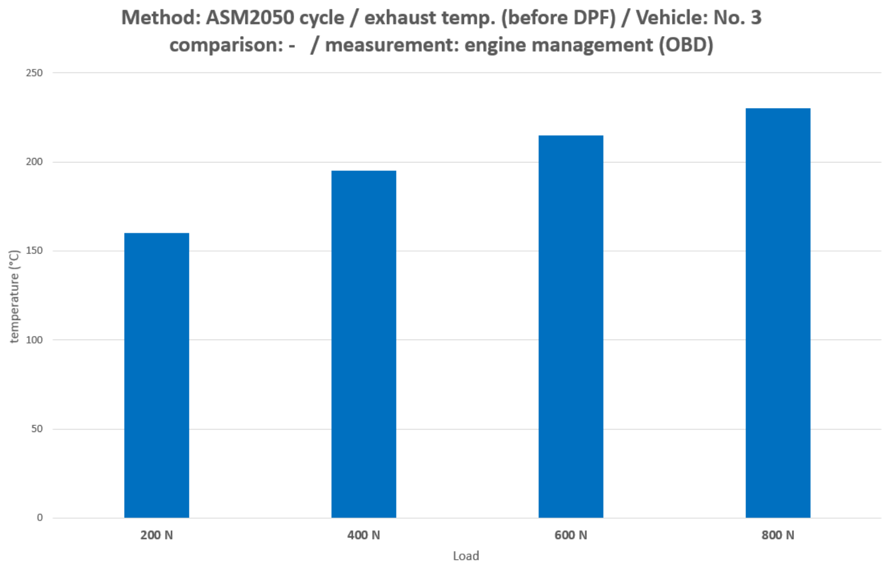


Figure 155: VEHICLE3 ASM2050, further investigation exhaust temperatue depending on load

Problems with the specific vehicle:

None. Measurements are done at 4WD – Dyno, so all wheels are turning at the more or less same speed.

5.3.5.3. DT80

Procedure:	**DT80 cycle**	(with different load)
Vehicle:	**No.3**	(Kia Sportage 2,0 DTCi, Euro 6)
Measurement:	**PEMS**	
Version:	2 / 2017.05.18	

Comparison: with/without defect

Some examples for driving cycles with different load, record of NOx:

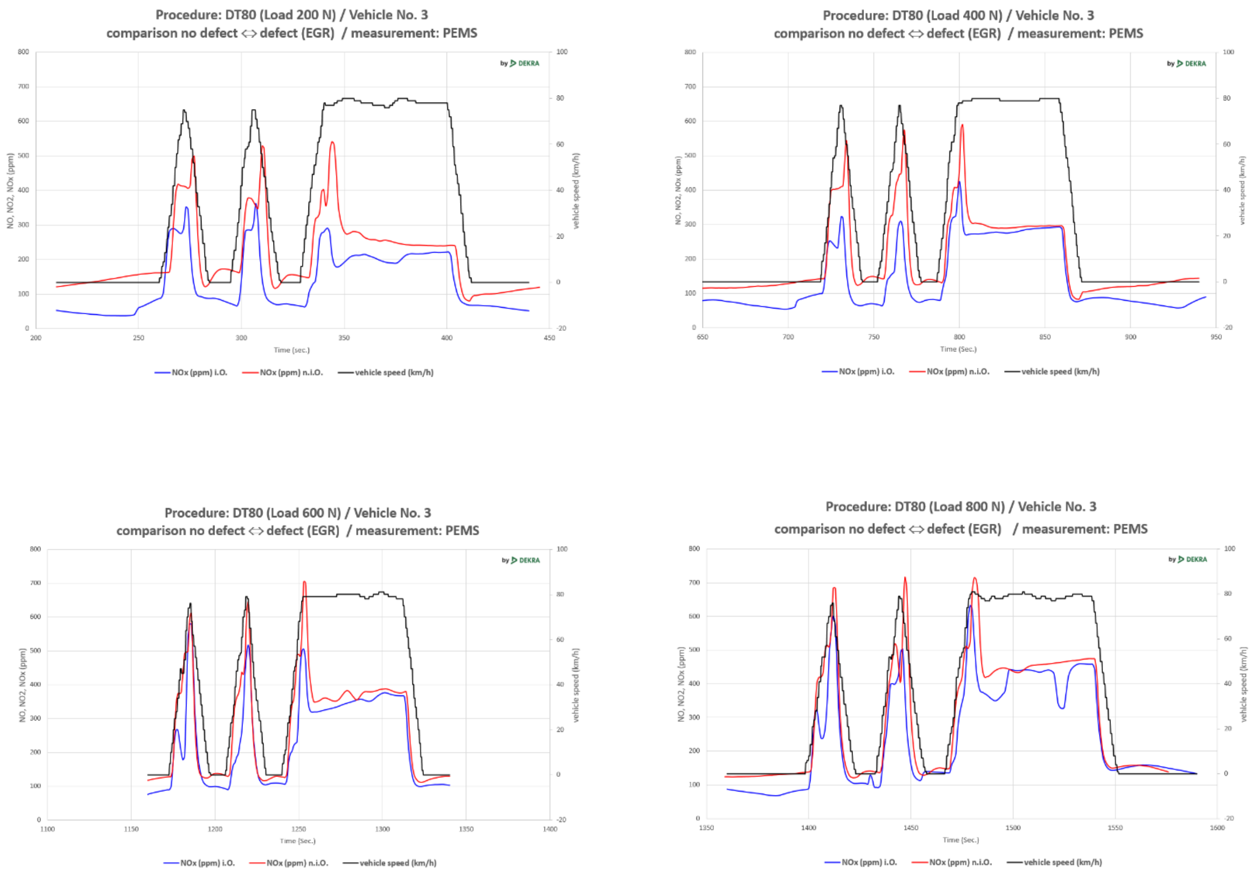


Figure 156: VEHICLE3 DT80, comparison with and without failure

Summary of the DT80 test (vehicle 3):
(mean values of 2 cycles each)

Measurement PEMS:

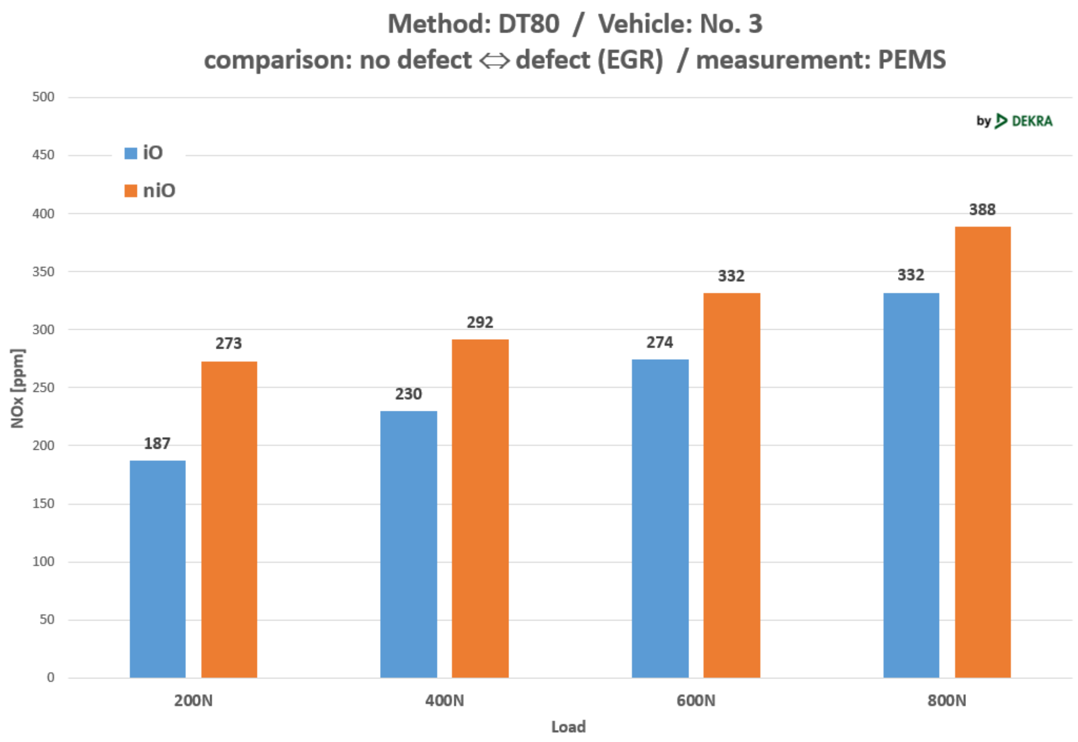


Figure 157: VEHICLE3 DT80, sumary

Ratio between vehicle i.o. and vehicle with defect:

	200 N	400 N	600 N	800 N
Ratio n.i.o./i.o.	1,5	1,3	1,2	1,2

Table 53: VEHICLE3 DT80, ratio with and without failure

→ The differences between "not defect" and "defect" are not very significant for this vehicle. As well at low load as at high load.

Further Investigations

No.

Problems with the specific vehicle:

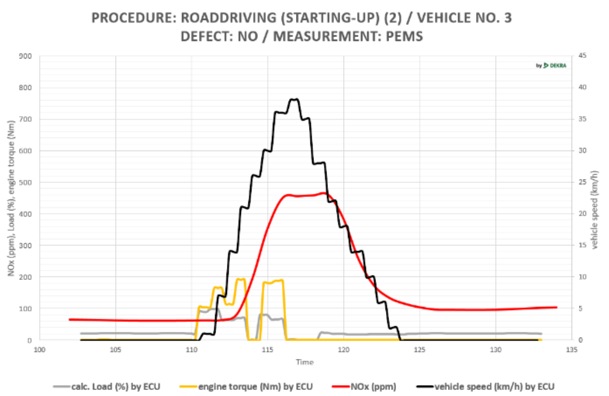
No.

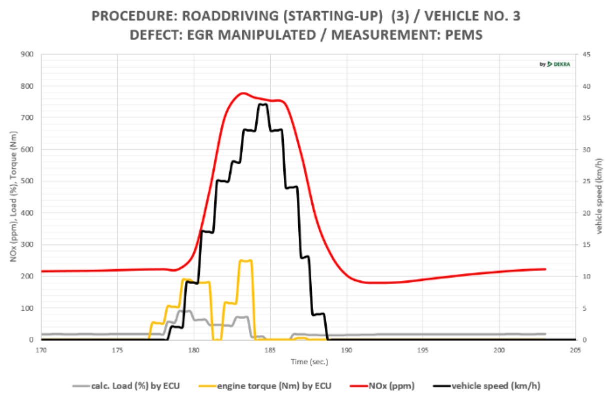
Short Road Driving

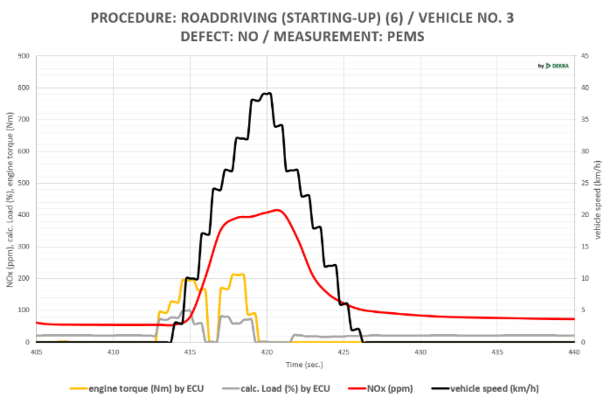
Procedure:	**short road driving (starting)**	
Vehicle:	**No.3**	(Kia Sportage 2,0 DTCi, Euro 6)
Measurement:	**PEMS** (and other)	
Version:	1 / 2017.08.01	

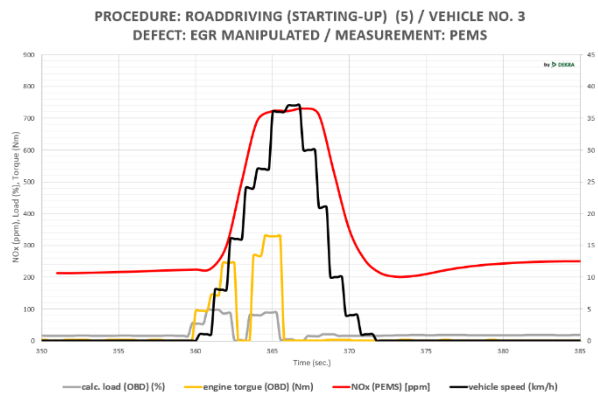
The “procedure” was a simple start-up and speed up in the first gear. Shift into the second gear and also accelerate. The vehicle thus reached a maximum speed of 30 to 45 km/h at a distance of about 300 meters. The acceleration was in this case (vehicle 3) relatively strong (between 1,7 and 2,2 m/s²) The track was almost flat. The points without load/torque in the graphs are the points of shifting (gear 1 – gear 2).

Comparison: without defect (left side) / with defect (right side)

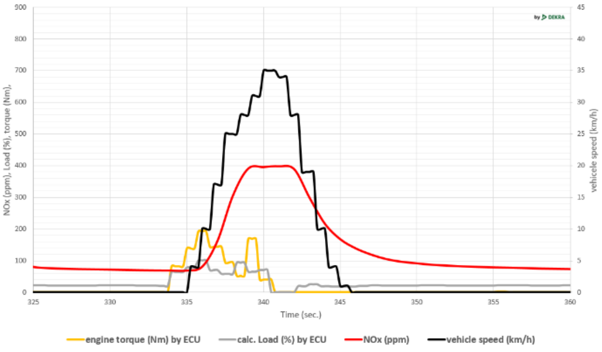




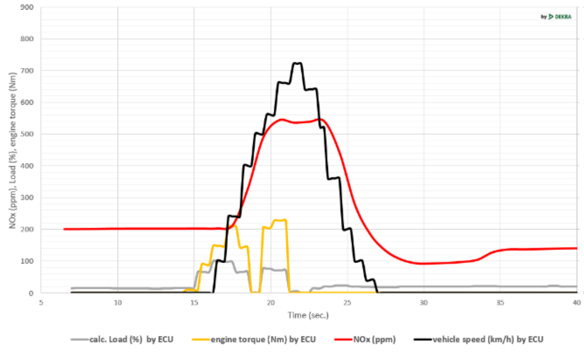




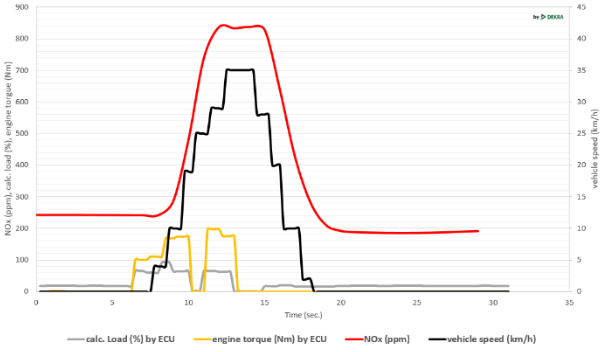
PROCEDURE: ROADDRIVING (STARTING-UP) (5) / VEHICLE NO. 3
DEFECT: NO / MEASUREMENT: PEMS



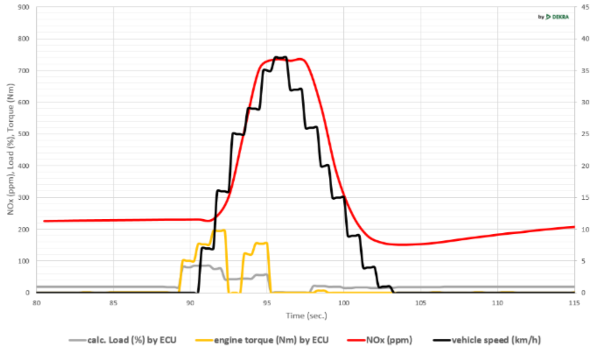
PROCEDURE: ROADDRIVING (STARTING-UP) (1) / VEHICLE NO. 3
DEFECT: NO / MEASUREMENT: PEMS



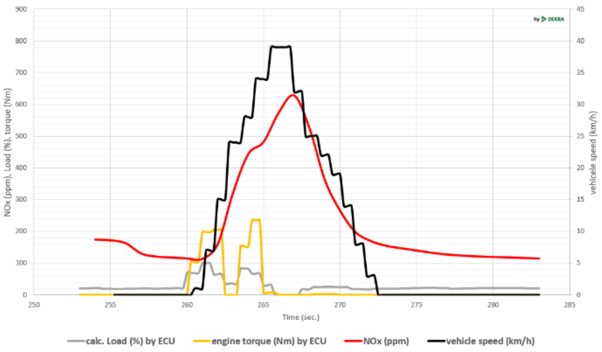
PROCEDURE: ROADDRIVING (STARTING-UP) (1) / VEHICLE NO. 3
DEFECT: EGR MANIPULATED / MEASUREMENT: PEMS



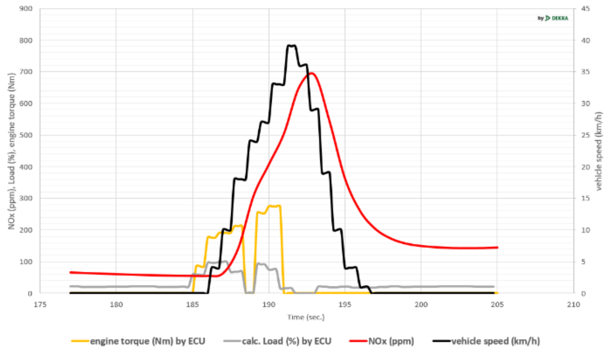
PROCEDURE: ROADDRIVING (STARTING-UP) (2) / VEHICLE NO. 3
DEFECT: EGR MANIPULATED / MEASUREMENT: PEMS



PROCEDURE: ROADDRIVING (STARTING-UP) (4) / VEHICLE NO. 3
DEFECT: NO / MEASUREMENT: PEMS



PROCEDURE: ROADDRIVING (STARTING-UP) (3) / VEHICLE NO. 3
DEFECT: NO / MEASUREMENT: PEMS



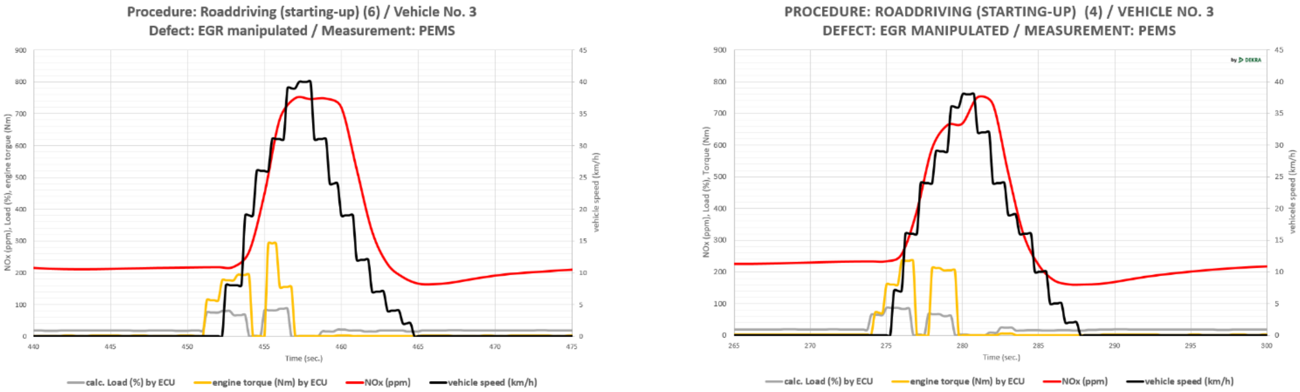


Figure 158: VEHICLE3 Short Test Drive, comparison with and without failure

To compare the road trips, we tried to cluster them by the engine load. For this we have recorded the calculated load and the calculated torque from the ECU by a diagnostic tool.
To verify these parameters we calculated the acceleration of the vehicle (maximum speed devided by the time to reach the maximum speed) and sorted the graphs above from lower acceleration (about 1,7 m/s², 1st row) to higher acceleration (about 2,2 m/s², last row).
As seen in the graphs, the load and the torque from the ECU is difficult to validate. There is less correlation to the acceleration of the vehicle and – for the study much more relevant – to the emission of NOx.

Summary of the road driving test (vehicle 3):

There are a significant higher level of NOx emissions, when the vehicle is defect (EGR, see chapter 4). Right column (defect) to left column (original). This effect seems to be clearer at lower acceleration/load.

Ratio between vehicle i.o. and vehicle with defect:

Acceleration:	1,7 m/s²	1,8 m/s²	1,95 m/s²	2,0 m/s²	2,1 m/s²	2,2 m/s²
Ratio n.i.o./i.o.	1,7	1,8	2,1	1,4	1,1	1,2

Table 54: VEHICLE3 Short Test Drive, ratio with and without failure

There is a need for more investigations in the possibility for real road drivings. These short tests are very dynamic and for this is needed a very good measurement of all relevant parameters with a very high resolution.

Further Investigations

Additional using of a 4/5-Gas analyzer with an electrochemical cell (in this case a AVL-DiTest “Gas 1000” with the option “NOx”). In the 1st examples is also shown the measured NO(x) values of the AVL device (Type “Gas1000” with option NOx, a electrochemical sensor).

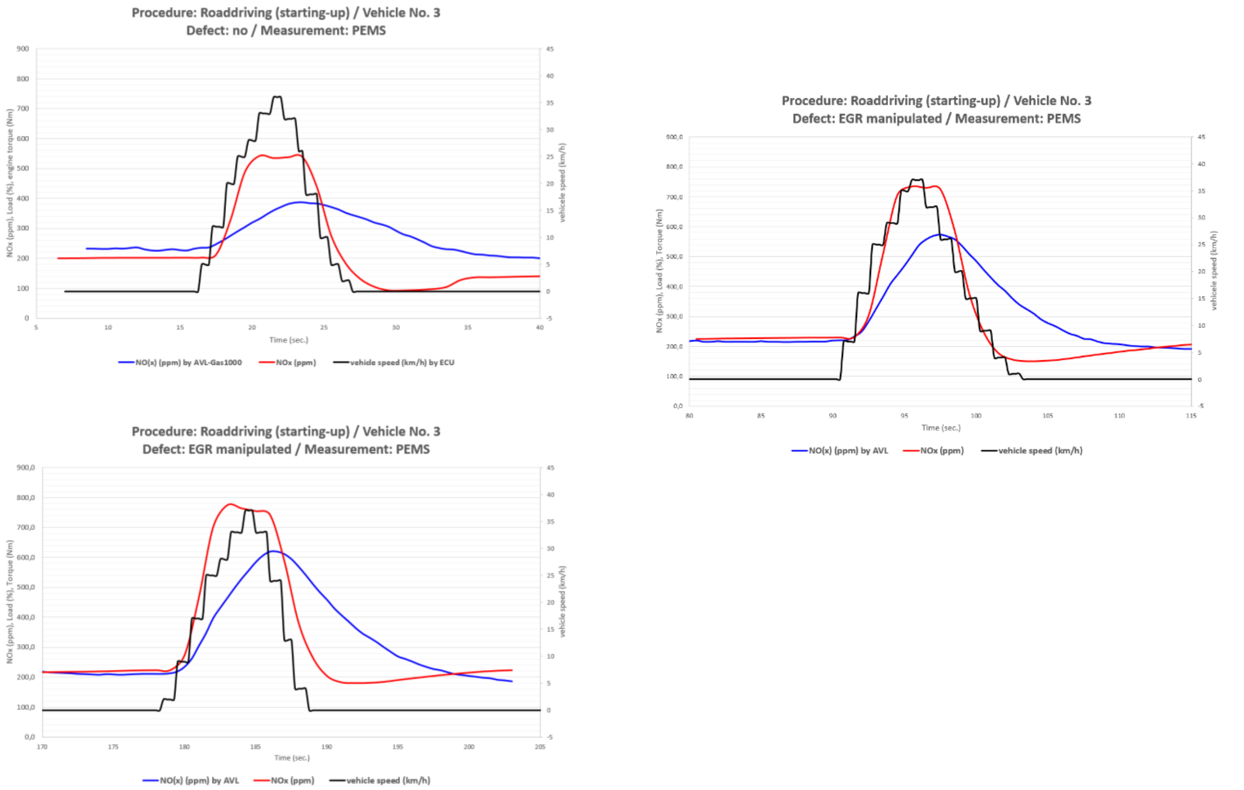


Figure 159: VEHICLE3 Short Test drive, further investigation

The AVL-DiTest “Gas 1000” device uses only a NO sensor and is calculating NOx by a known NO2/NO ratio. This is working (compared to a well calibrated PEMS) very good at low idle, but shows always lower values at higher engine/vehicle speed (load ?).
Also the measurement devices with electrochemical sensors in the moment seems to be too inert for dynamic test procedures. Further investigations are necessary.

Problems with the specific vehicle:

No. Measurements are done at 4WD – Dyno, so all wheels are turning at the more or less same speed.

5.3.5.4. Capelec Evaluation

Procedure:	**CAPELEC method**	
Vehicle:	**No.3**	(Kia Sportage 2,0 DTCi, Euro 6)
Measurement:	**PEMS**	
Version:	2 / 2017.05.18	

Comparison: with/without defect

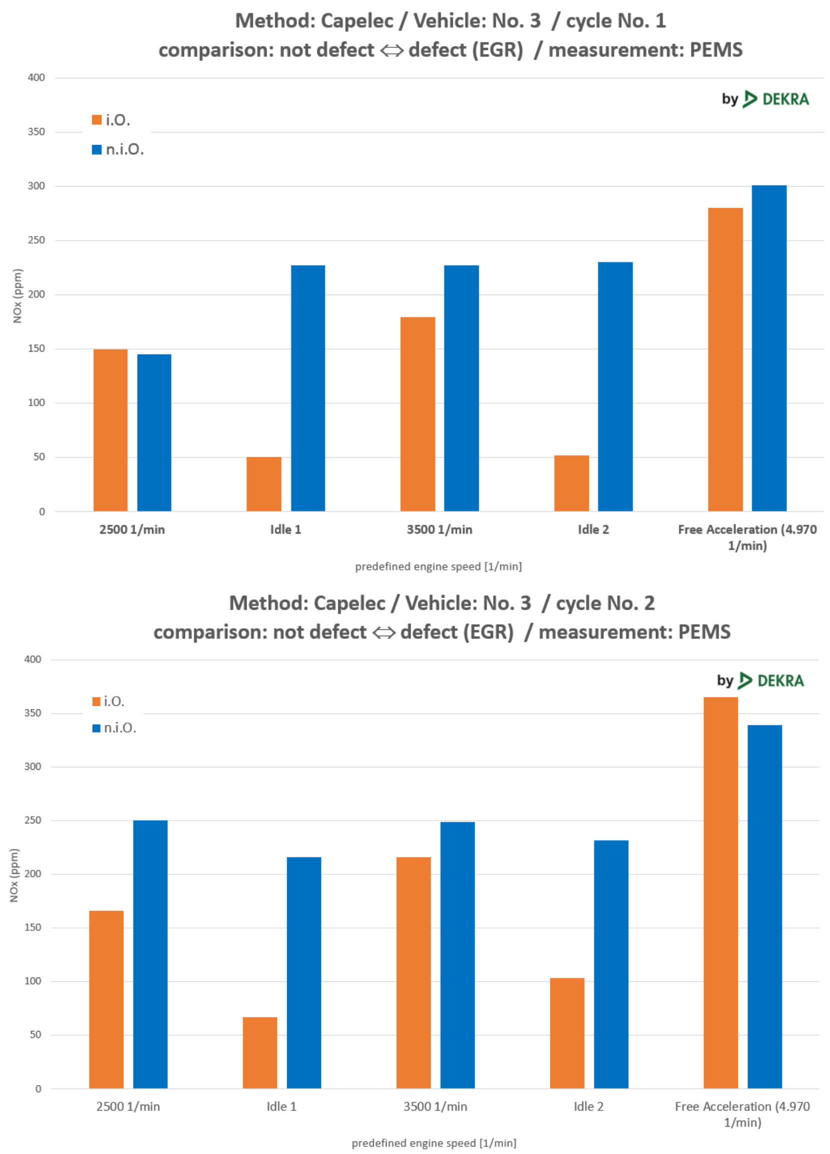


Figure 160: VEHICLE3 Capelec cycle, comparison with and without failure

<u>Idle speed:</u> the differences between "not defect" and "defect" are significant. If the EGR-System works correct (state "not defect"), the EGR valve is open at idle speed. This means low NOx. As the EGR is reduced in the state "defect", there is high NOx.
<u>3.500 1/min:</u> the EGR valve is reduced/closed at this speed also if the system works proper. That means there is no/not a big difference between not defect/defect.
<u>Free acceleration:</u> see 3.500 1/min. At that speed the EGR valve is closed in general. That means no big difference between not defect/defect. As the load is higher the measured NOx is higher than at (constant) 3.500 1/min.
<u>2.500 1/min:</u> the EGR valve is normally open or partial open (see idle speed). That means there should be a significant difference between not defect and defect (EGR manipulated), but on a higher level than at idle speed.

Further Investigations

Function of EGR

The following chart shows the function of EGR at the capelec method.
At idle speed and at "high idle" (2.500 1/min) EGR is in function. At 3.500 1/min and at cut-off speed (free acceleration) the EGR valve is closed.
For the engine speed at 3.500 1/min, see chapter 3: problems with this specific vehicle.

The exhaust temperature increases only at "free acceleration" considerable (150 °C to 202 °C)

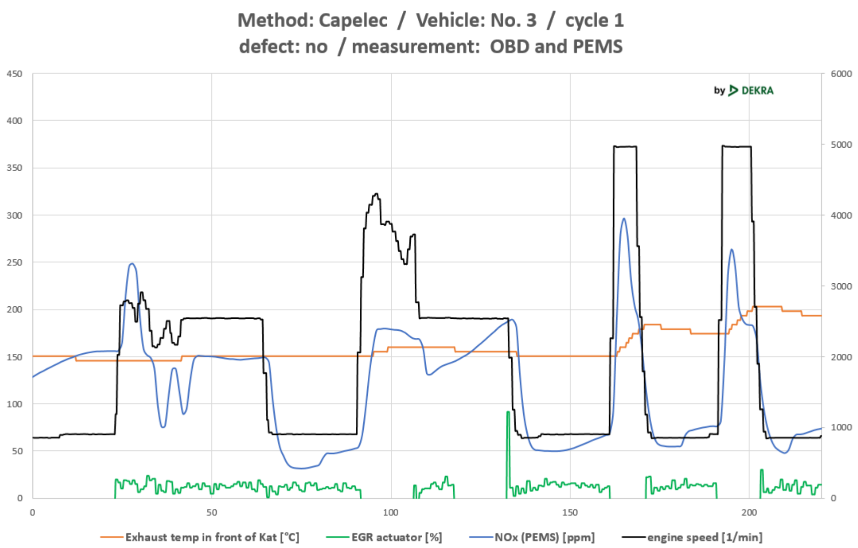


Figure 161: VEHICLE3 Capelec Cycle, further investigation function of EGR

Effect of increasing temperatures:

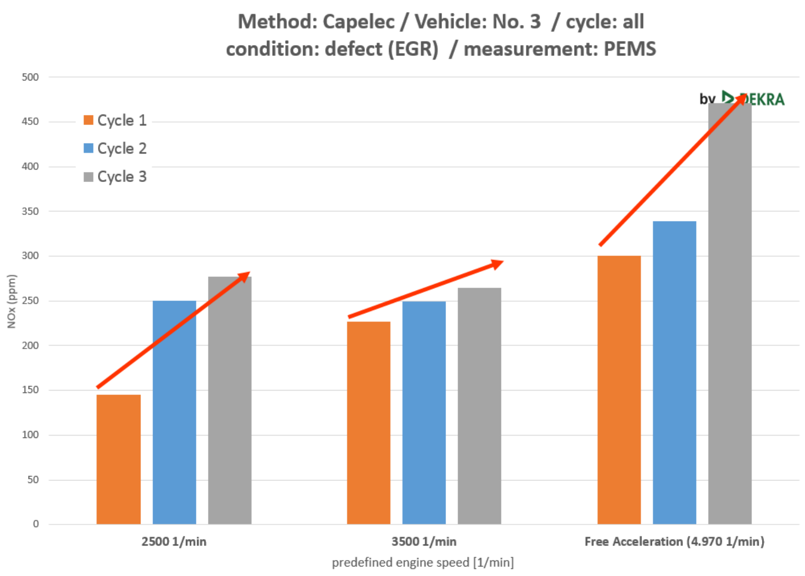


Figure 162: VEHICLE3 capelec cycle, further investigation effect of increasing temperature

We see this effect for principal at all test methods (ASM2050, DT80, AVL,…)

Problems with the specific vehicle:

- Vehicle is equipped with an 'engine speed limitation' at standing wheels (2.500 1/min).
  There was no way (found) to de-activate this function.
  - for the tests/investigations the vehicle was placed on a 4-wheel dyno and driven by this dyno (at 15 km/h)
  - with this "preparation" and (!) with pressed clutch, it was possible to do a "free acceleration" (4.970 1/min)
  - Nevertheless this "preparation" it was not possible to keep 3.500 1/min (or higher) for a longer time than 4-5 seconds. The engine speed automatically reduces down to 2.500 1/min by the engine management.
  - because of this fact, stable conditions are difficult or not possible

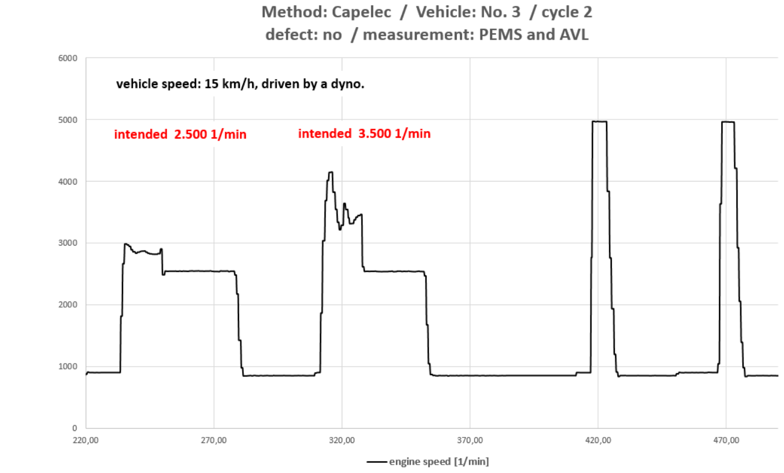


Figure 163: VEHICLE3 Capelec Cycle, engine speed limitation

5.3.5.5. AVL Evaluation

Procedure:	**AVL method**	
Vehicle:	**No.3**	(Kia Sportage 2,0 DTCi, Euro 6)
Measurement:	**PEMS and AVL**	
Version:	1 / 2017.05.22	

Comparison: with/without defect

Measurement: PEMS:

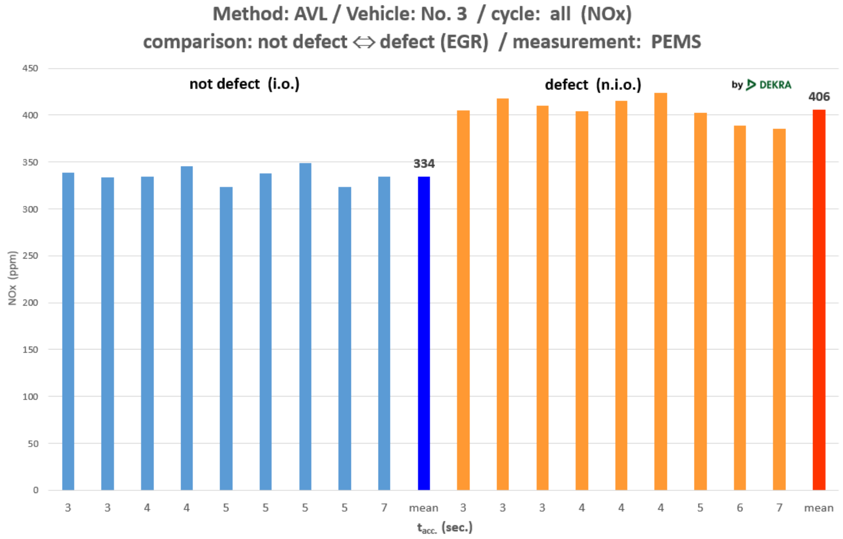


Figure 164: VEHICLE3 AVL cycle, comparison with and without failure (measurement PEMS)

Measurement AVL:

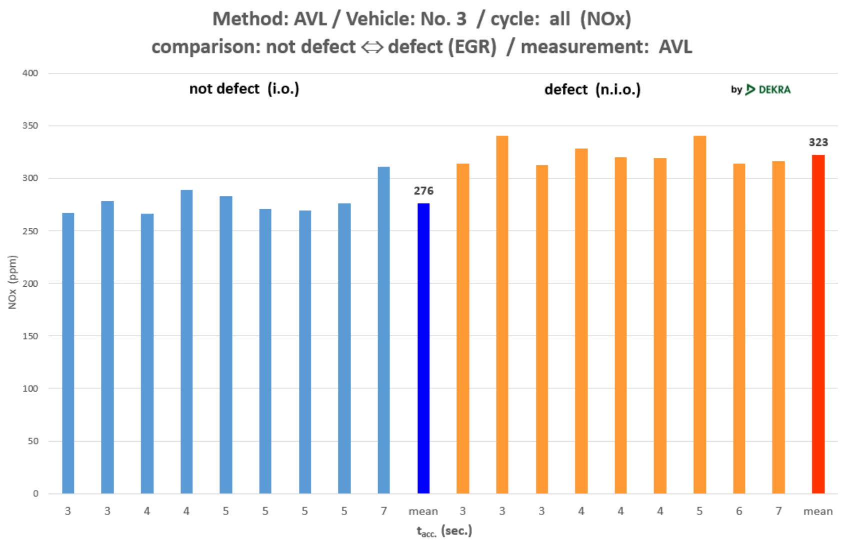


Figure 165: VEHICLE3 AVL cycle, comparison with and without failure (measurement AVL equipment)

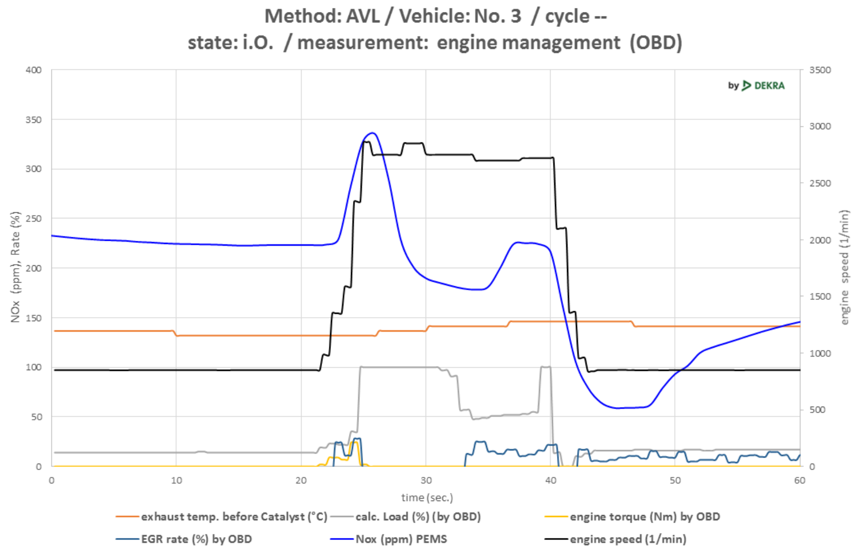
Ratio between vehicle i.o. and vehicle with defect (n.i.o.):

	PEMS	AVL
Ratio n.i.o./i.o. (referred to the mean values)	1,2	1,2

Table 55: VEHICLE3 AVL cycle, ratio with and without failure (measurement PEMS and AVL equipment)

Further Investigations

Example for a “slow” acceleration (4 seconds) up to 2.500 1/min (+/- 150 1/min). All data are from the engine management via a diagnostic tool.



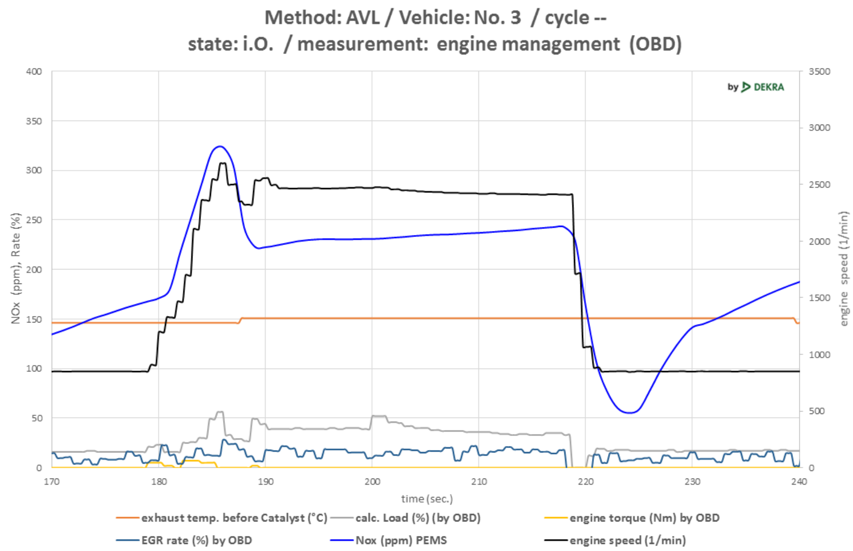


Figure 166: VEHICLE3 AVL cycle, further investigation, slow acceleration

The EGR rate depends mainly at the “load”. This load is calculated by the ECU (engine management) depending on some sensor signals (mainly air mass).

The exhaust temperature is at idle speed below 140 °C and increases at this slow acceleration very low up to max. 150 °C

Problems with the specific vehicle:

- (see also the investigations for the CAPELEC method)
- as the AVL method needs only “high idle” speed (2.500 1/min) and the vehicle 3 is limited at this engine speed, it is much easier to do the AVL method.
- Nevertheless for the investigations the vehicle was placed on a 4 wheel dyno, to have realistic conditions regarding the practice in doing the AVL method and regarding the engine management.

5.3.6. Lab tests Vehicle 4

5.3.6.1. Installed failure

Vehicle No. 4 is a vehicle with Euro 6c. It is equipped with an EGR, an Oxi-Kat + DPF (catalytically active) and a SCR-System. At the moment the highest level of after treatment system solution.

The installed failure for this vehicle was to manipulate the EGR-system by blocking it. Only a small hole (4mm) was open.

The OBD-system did't detect this defect while the time of measuring (many engine starts, driving on the 4-weel-dyno and on the road).

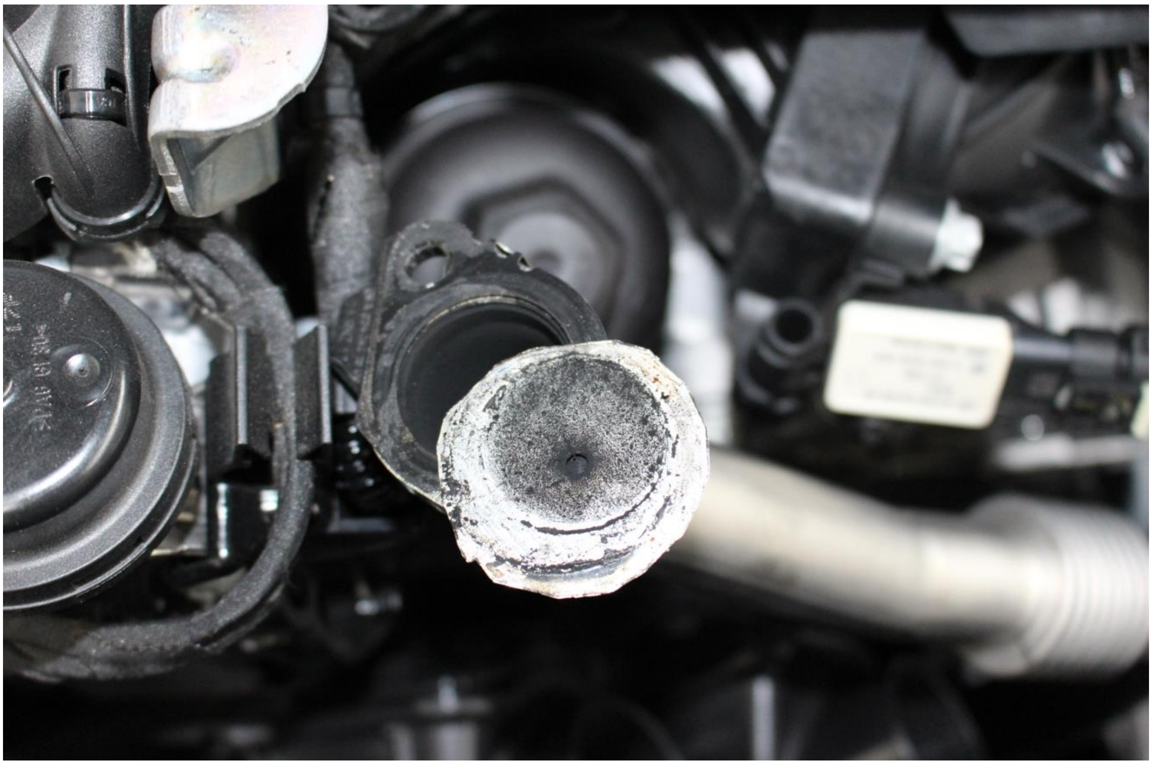


Figure 167: VEHICLE4, Installed failure

5.3.6.2. ASM2050

Procedure:	**ASM2050**	(with different Load)
Vehicle:	**No.4**	(Mercedes E 220D, EGR, Oxi-Cat + DPF (catalytically active), SCR-System, Euro 6c)
Measurement:	**PEMS** (and other)	
Version:	1 / 2017.12.29	

Comparison: with/without defect

Some examples for driving cycles with different (extra) load, record of NOx

without defect

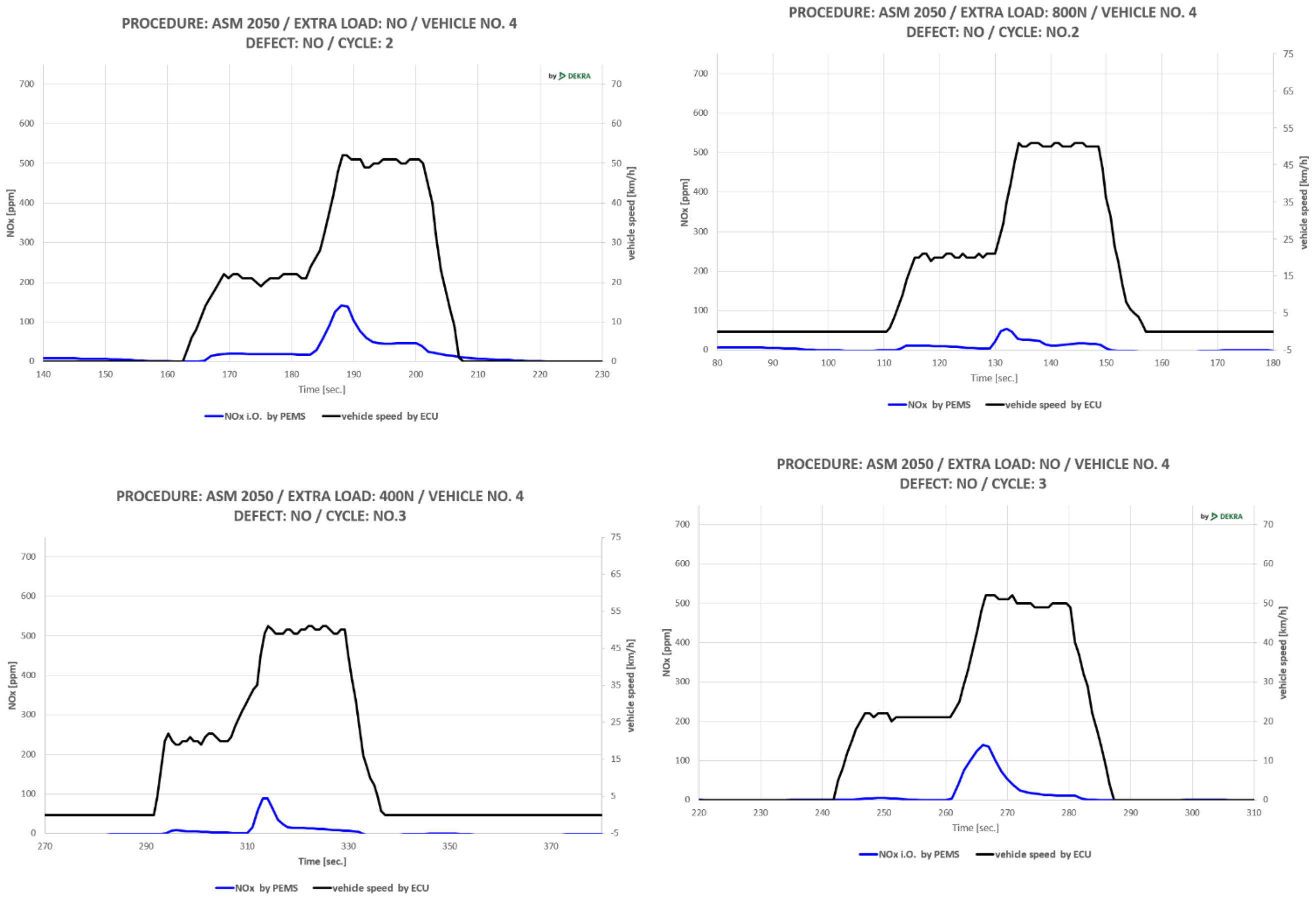


Figure 168: VEHICLE4 ASM2050, without defect

→ no higher NOx values with higher load !
→ vehicle 4 (Euro 6c, new vehicle) shows very low NOx

with defect

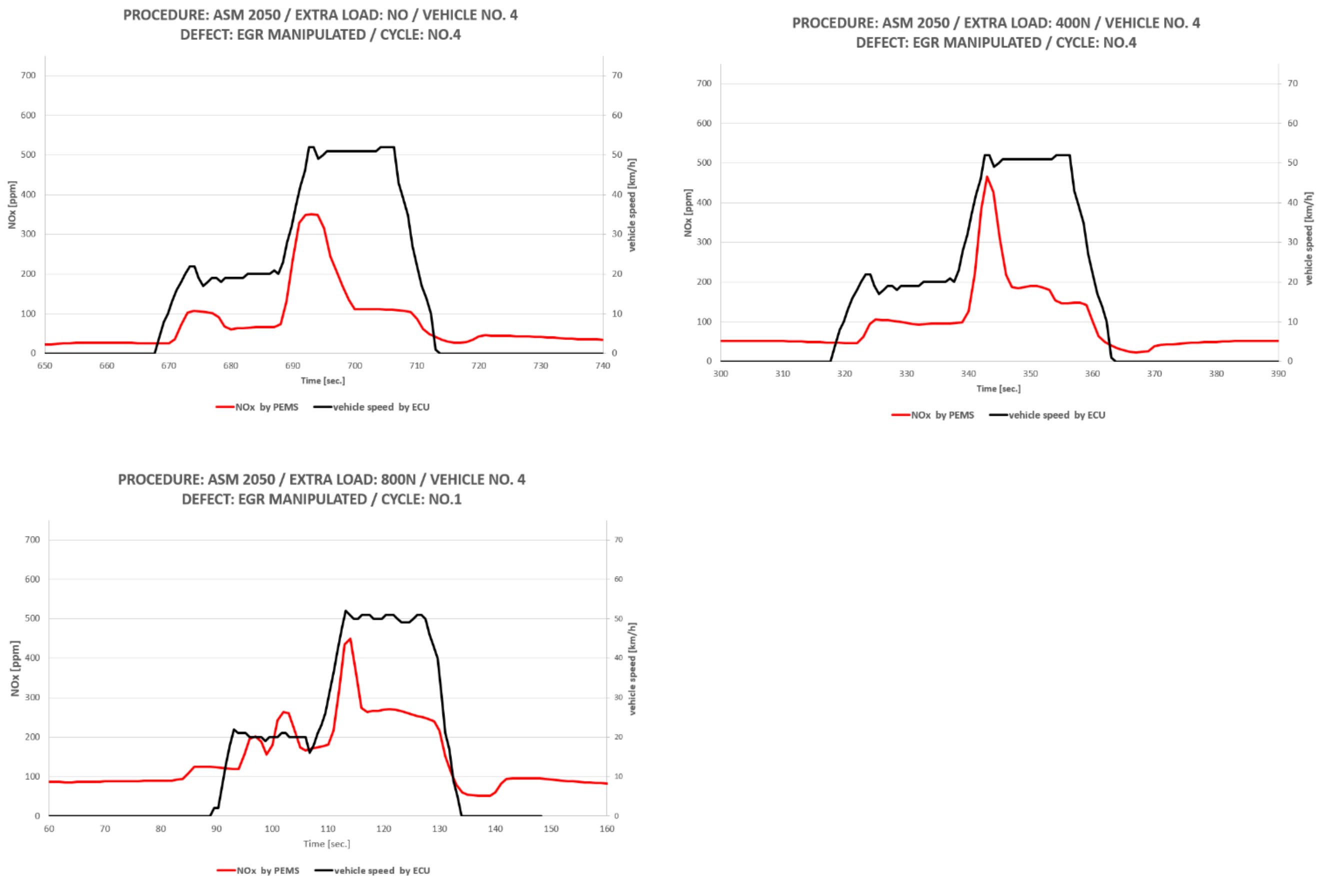


Figure 169: VEHICLE4 ASM2050, with defect

→ significant higher values with build in defect
→ peak-values seems to depend <u>not</u> very much from the load. See also “without defect”
This means low load seems to be sufficient

Direct comparison with/without defect

These measuring’s (with/without defect) was performed at the well defined cycles, it was always the same driver and shown is for both cases always the same cycle (No. 4). With this illustration you can see the different levels for NOx very clear.

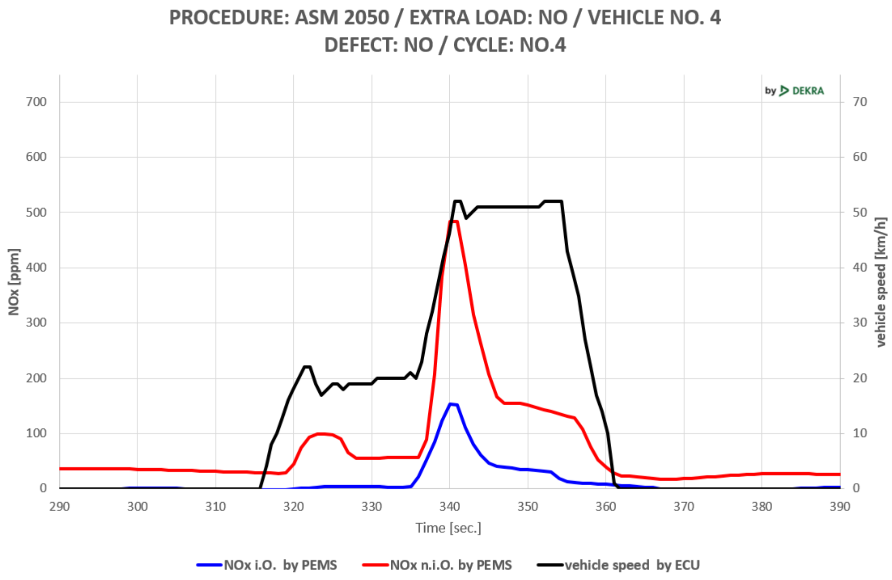


Figure 170: VEHICLE4 ASM2050, comparison with and without defect

→ significant higher level of NOx with defect.

Total and mean values, vehicle 4, ASM 2050

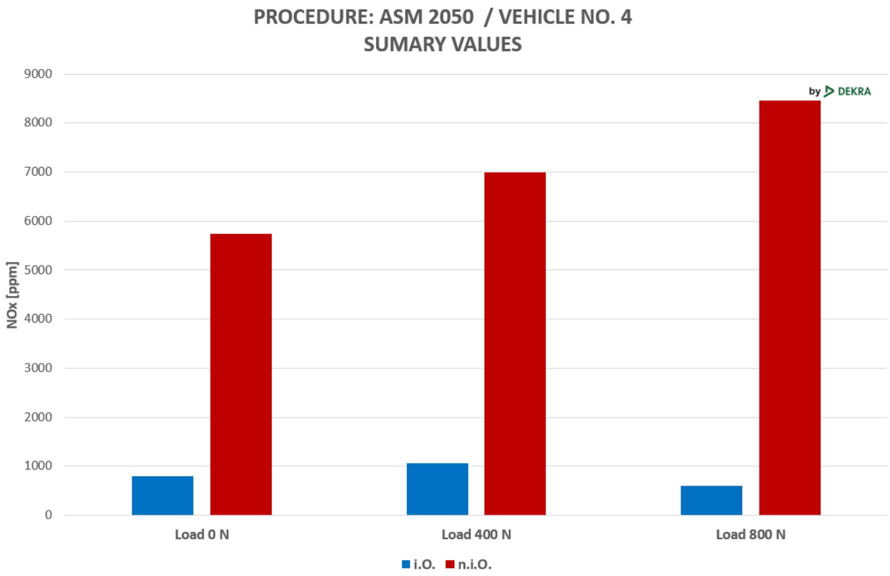


Figure 171: VEHICLE4 ASM2050, summary values

Total ppm over the ASM2050-cycles (always mean of 3 cycles)

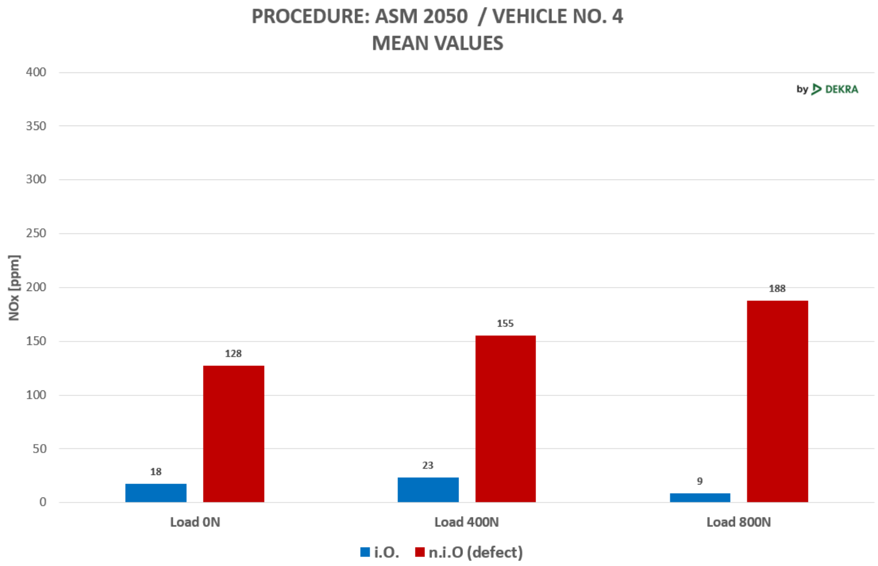


Figure 172: VEHICLE4 ASM2050, mean values

Mean values of the ASM2050-cycles (always mean of 3 cycles)

Ratios with/without defect:

The table/ratios are relevant for the total values as well as for the mean values (see graphs above)

	0 N	400 N	800 N
Ratio n.i.o./i.o.	**7,1**	**6,5**	**14,2**

Table 56: VEHICLE4 ASM2050, ratio with and without defect

→ very good detection of defects/failures at high load and at low load

Further Investigations

None

Problems with the specific vehicle

Measurements was performed at an 4WD – Dyno, so all wheels are turning at the more or less same speed.

5.3.6.3. Short Road Driving

Procedure:	Road - driving (Starting-up)	
Vehicle:	**No.4**	(Mercedes, E 220D EGR, Oxi-Cat + DPF (catalytically active), SCR-System, Euro 6c)
Measurement:	**PEMS** (and other)	
Version:	1 / 2017.12.28	

Comparison: with/without defect

Every "cycle" was a short and "smooth" acceleration up to 20 km/h (target) and after this a rank (maneuver) for positioning the vehicle in the right direction/change the direction.

without defect

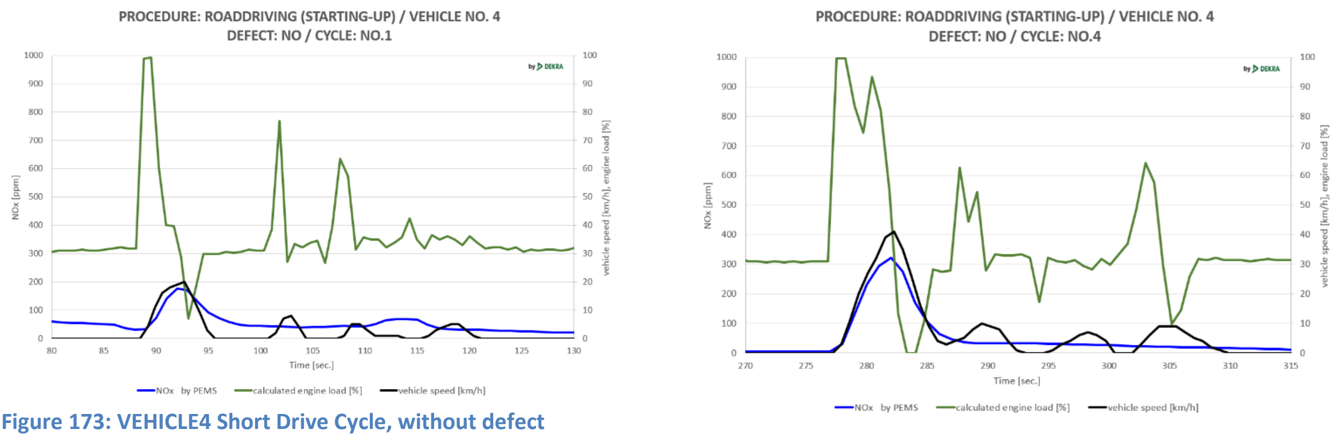


Figure 173: VEHICLE4 Short Drive Cycle, without defect

with defect

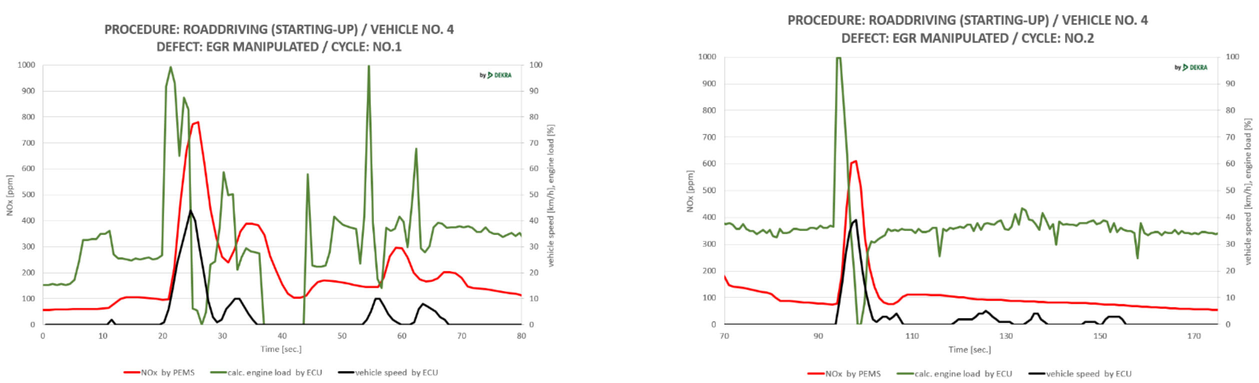


Figure 174: VEHICLE4 Short Drive Cycle, with defect

→ All in all very low values for this vehicle (Euro 6c), compared to all other investigated vehicles
→ higher level of NOx for the vehicle with installed defect, but the impact of the defect (EGR manipulated, see No. 4) is not very high.
→ in some cases no increasing of NOx is explainable by the "smooth" drivings/accelerations and for this only low engine load (see charts)
→ For this vehicle (vehicle 4) it seems that there is a minimum of 80% of engine load needed to detect NOx

Summary of the Roaddriving / start-up tests (vehicle 4):
(mean values of 4 cycles each (peaks))

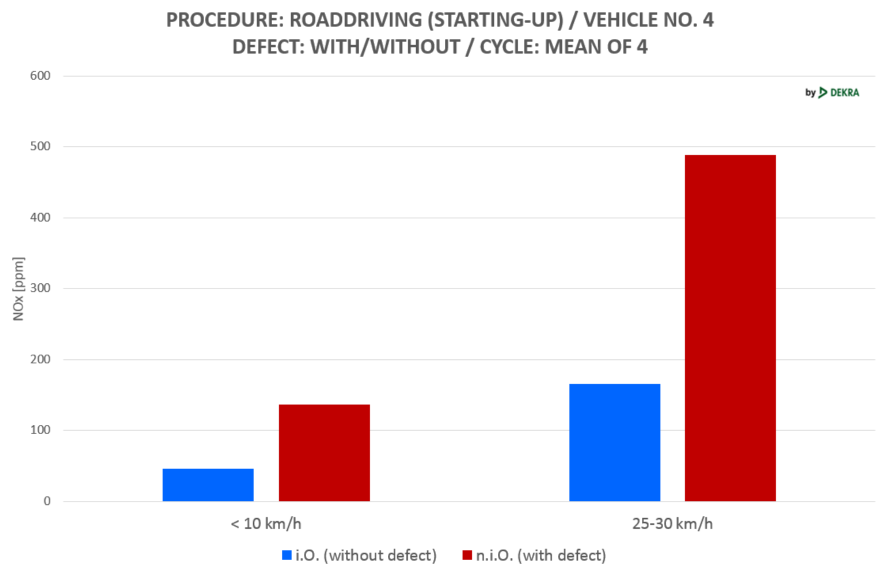


Figure 175: VEHICLE4 Short Drive Cyclemean values

Ratio between vehicle i.o. and vehicle with defect:

	25-30 km/h	< 10 km/h
Ratio n.i.o./i.o.	**3,0**	**3,0**

Table 57: VEHICLE4 ASM2050, ratio with and without defect

→ For vehicle 4 are measured very low NOx values (Euro 6c).
For this there is a need of a high accuracy of measurement and high engine load !
→ To detect NOx for this vehicle is a minimum of 80% of engine load needed.
This "engine load" is out of the ECU and is calculated by different input values.
The calculation is only known by the vehicle manufacturer and is not standardized
→ more investigations are necessary

Further Investigations

→ Engine load is available by the ECU, but not within the standardized OBD!
→ Engine load in combination with other relevant data, can help to get comparable conditions

Problems with the specific vehicle:

None.

5.3.7. Lab tests Vehicle 5

5.3.7.1. Installed failure

Vehicle No. 5 is a vehicle with Euro 6. It is not equipped with a SCR-system but with an LNT-catalyst (Lean Nox Trap). In addition it is equipped with an EGR-system

The installed failure for this vehicle was to manipulate the EGR-system, by removing a temperature sensor, so that a part of the led back exhaust gas is blowing out (ambient air) and is not coming to the intake air of the engine. As a result the EGR-rate is reduced.

By comparison with the other vehicles, this defect is a relative small defect.

Figure 176: VEHICLE5, installed failure

The OBD-System noticed this defect not direct, but after some tests on the dyno and some driving on the road at the end of the “test session” (about 100 km driving).

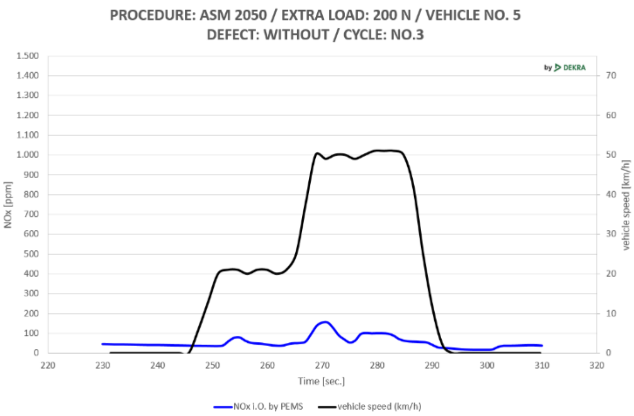
5.3.7.2. ASM2050

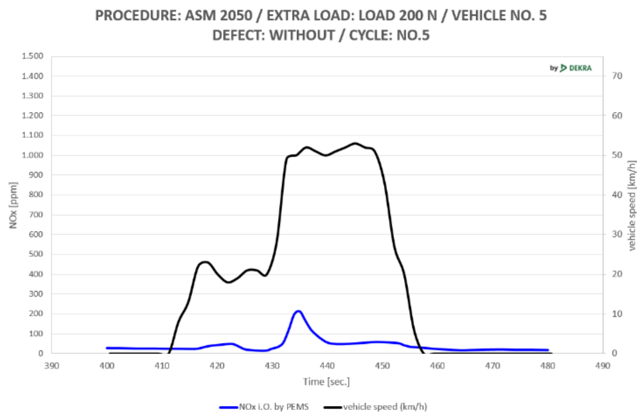
Procedure:	**ASM2050**	(with different Load)
Vehicle:	**No.5**	(BMW 116d, DPF+LNT, Euro 6)
Measurement:	**PEMS** (and other)	
Version:	2 / 2017.28.12	

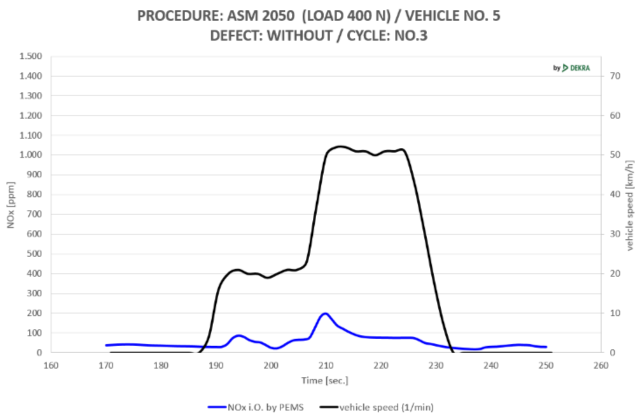
Comparison: with/without defect

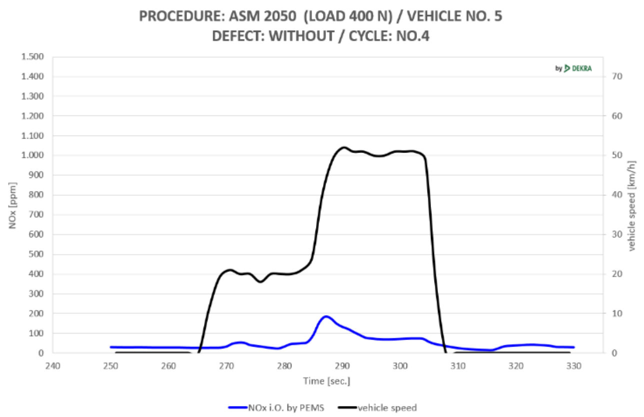
Some examples for driving cycles with different (extra) load, record of NOx

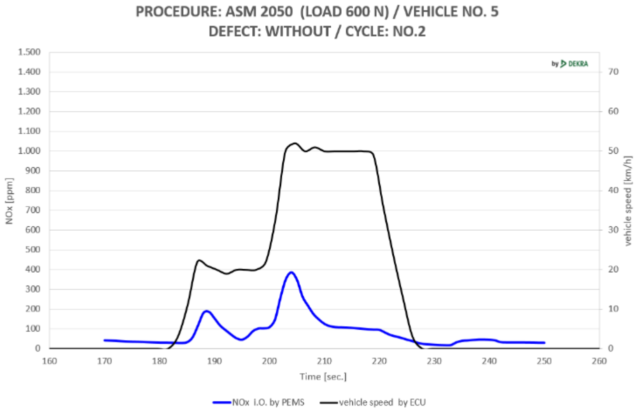
without defect











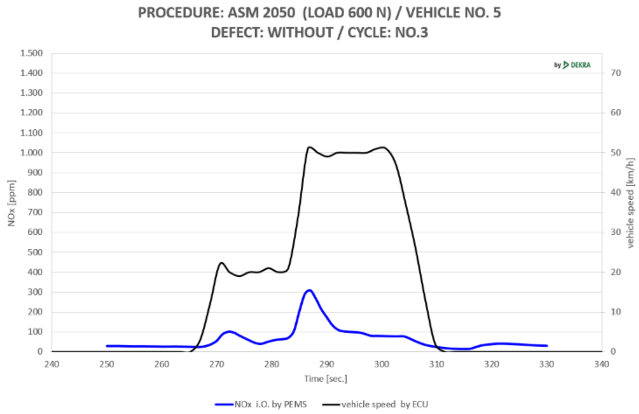
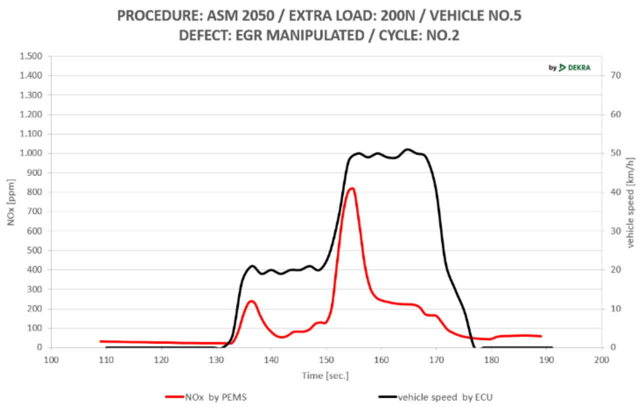
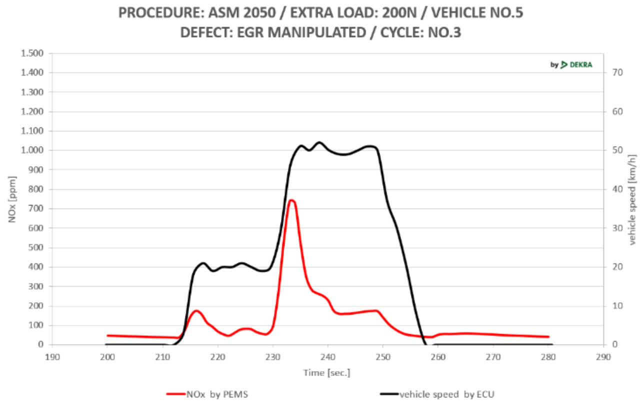


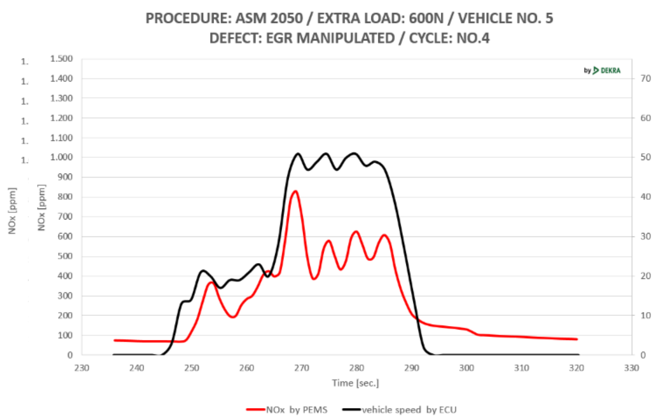
Figure 177: VEHICLE5 ASM2050, without defect

→ higher load is producing also higher NOx (200 up to 400ppm), but still very low compared with the failure impact.

with defect







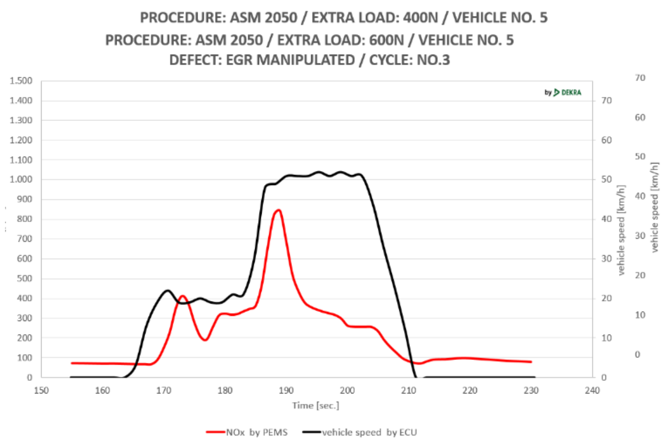
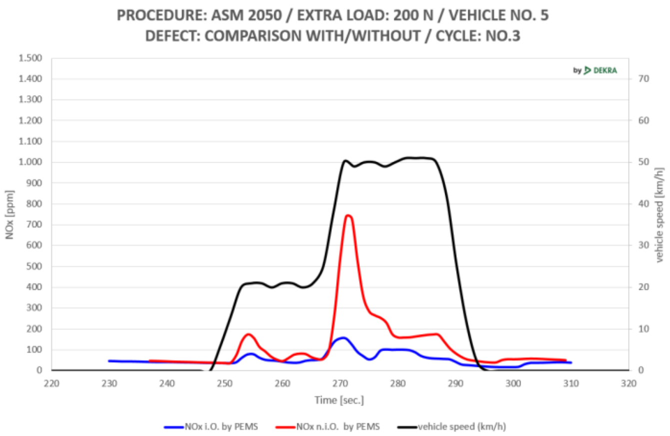


Figure 178: VEHICLE5 ASM2050, with defect

→ significant higher values with build in defect (700 up to 800ppm)
→ with defect: peak-values seems to depend not very much from the load
→ measurement has a very good resolution. Driving behavior can be recognized direct and evaluated.

Direct comparison with/without defect

These measurements (with/without defect) were performed at different dates and times. But the cycle was well defined, it was always the same driver and shown is for both cases always the same cycle (3, 4, 5,…). With this illustration you can see the different levels for NOx very clear.



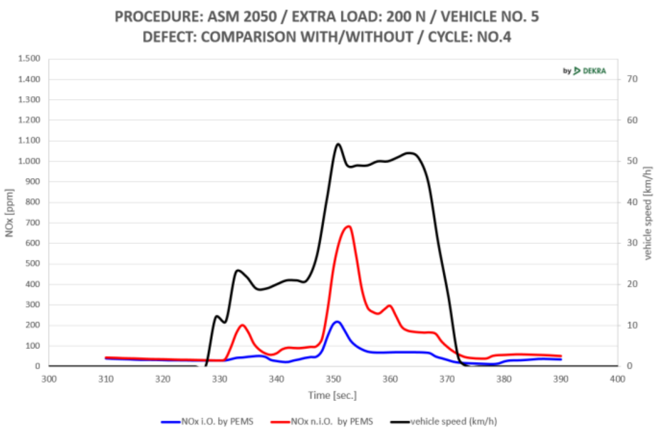


Figure 179: VEHICLE5 ASM2050, comparison with and without defect

→ with defect we have significant higher level of NOx. Although the installed failure is in this case (vehicle 5) with likely low impact (EGR, see chapter 4). The effect on NOx concentration is increasing at higher load.

Total and mean values, vehicle 5, ASM 2050

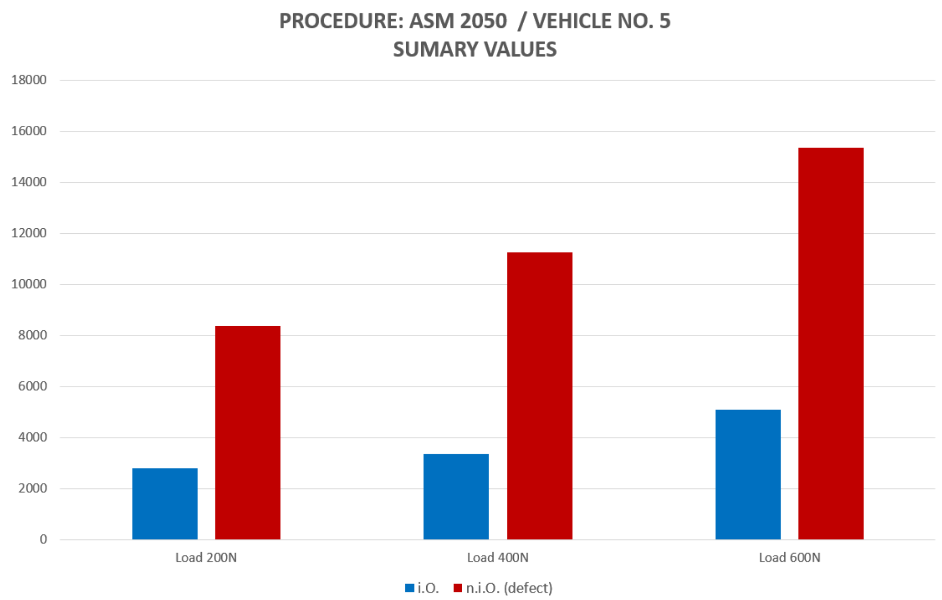


Figure 180: VEHICLE5 ASM2050, sumary values with and without defect

Total ppm/sec. over the ASM2050-cycles (always mean of 3 cycles)

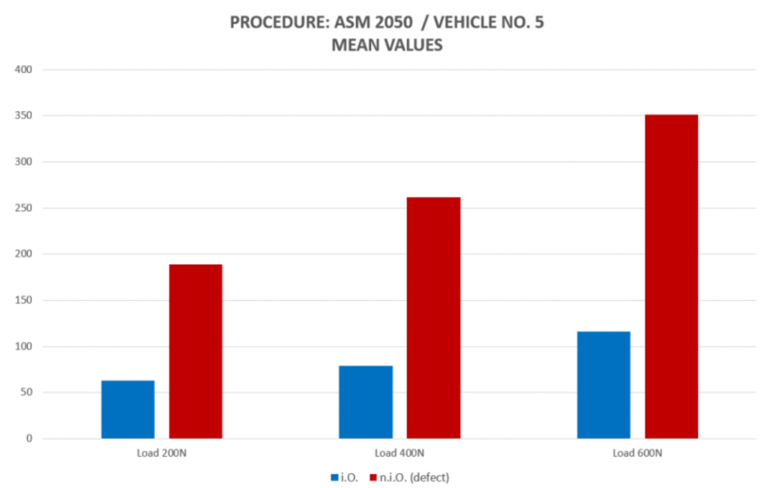


Figure 181: VEHICLE5 ASM2050, mean values with and without defect

Mean values of the ASM2050-cycles (always mean values out of 3 cycles)

Ratio with/without defect:

The table/ratios are relevant for the total values as well as for the mean values (see graphs above)

	200 N	400 N	600 N
Ratio n.i.o./i.o.	**3,0**	**3,3**	**3,0**

Table 58: VEHICLE5 ASM2050, ratio with and without defect

→ very good detection of defects/failures at high load and at low load. High load seems not be necessary.

Further Investigations

exhaust temperature (and load)

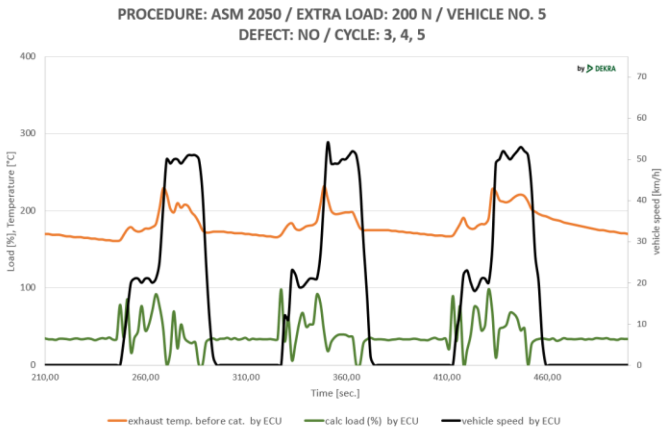


Figure 182: VEHICLE5 ASM2050, further investigation exhaust temperature and load (200N)

→ calculated engine load is normally available by the engine management, but <u>not</u> by the standardized OBD, therefore an generic scan tool can interrogate this value.

→ exhaust temperature at low load is also at low leve. Only in peaks over 200 °C

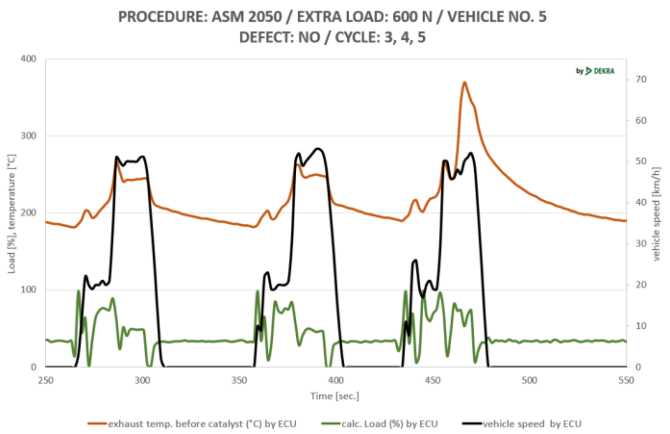
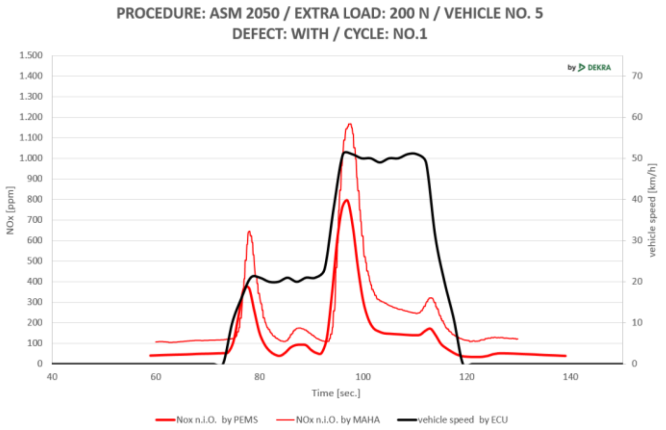


Figure 183: VEHICLE5 ASM2050, further investigation exhaust temperature and load (600N)

→ higher exhaust temperatures (mostly > 200°C) at higher load. Also higher amount of load (total)

Measurement

Additionally to the PEMS measurement a device from MAHA is used for the measurings. It was a 4-gas-analyzer (Type “MET 6.1/6.3”) with an chemical sensor for NO and an NO2.



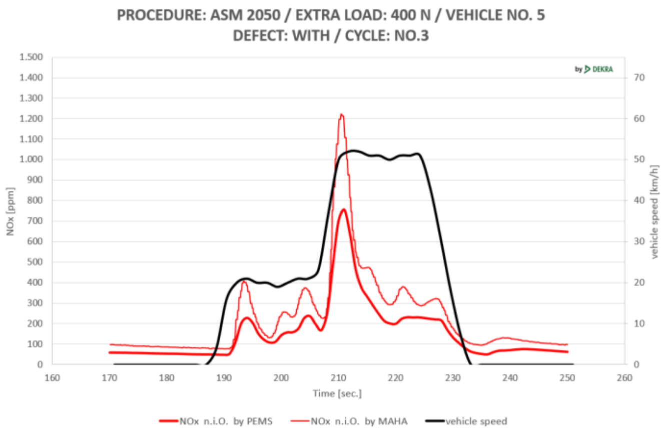


Figure 184: VEHICLE5 ASM2050, further investigation exhaust temperature and load

→ the NO/NO2-sensors was calibrated before the measurings (by MAHA). The values shows a very good resolution and a very good correlation to the PEMS, but we can see a constant offset of about 30% (always plus). Maybe a problem of the calibration (?)

Problems with the specific vehicle:

No. Measurements was performed at an 4WD – Dyno, so all wheels are turning at the more or less same speed.

5.3.7.3. Short Road Driving

Procedure:	Road driving (Starting-up)	
Vehicle:	**No.5**	(BMW 116d, DPF+LNT, Euro 6)
Measurement:	**PEMS** (and other systems)	
Version:	1 / 2017.06.11	

Comparison: with/without defect

Every "cycle" was a short rank (maneuver) for positioning the vehicle in the right direction/change the direction and after this an acceleration up to 30 km/h (target).

without defect

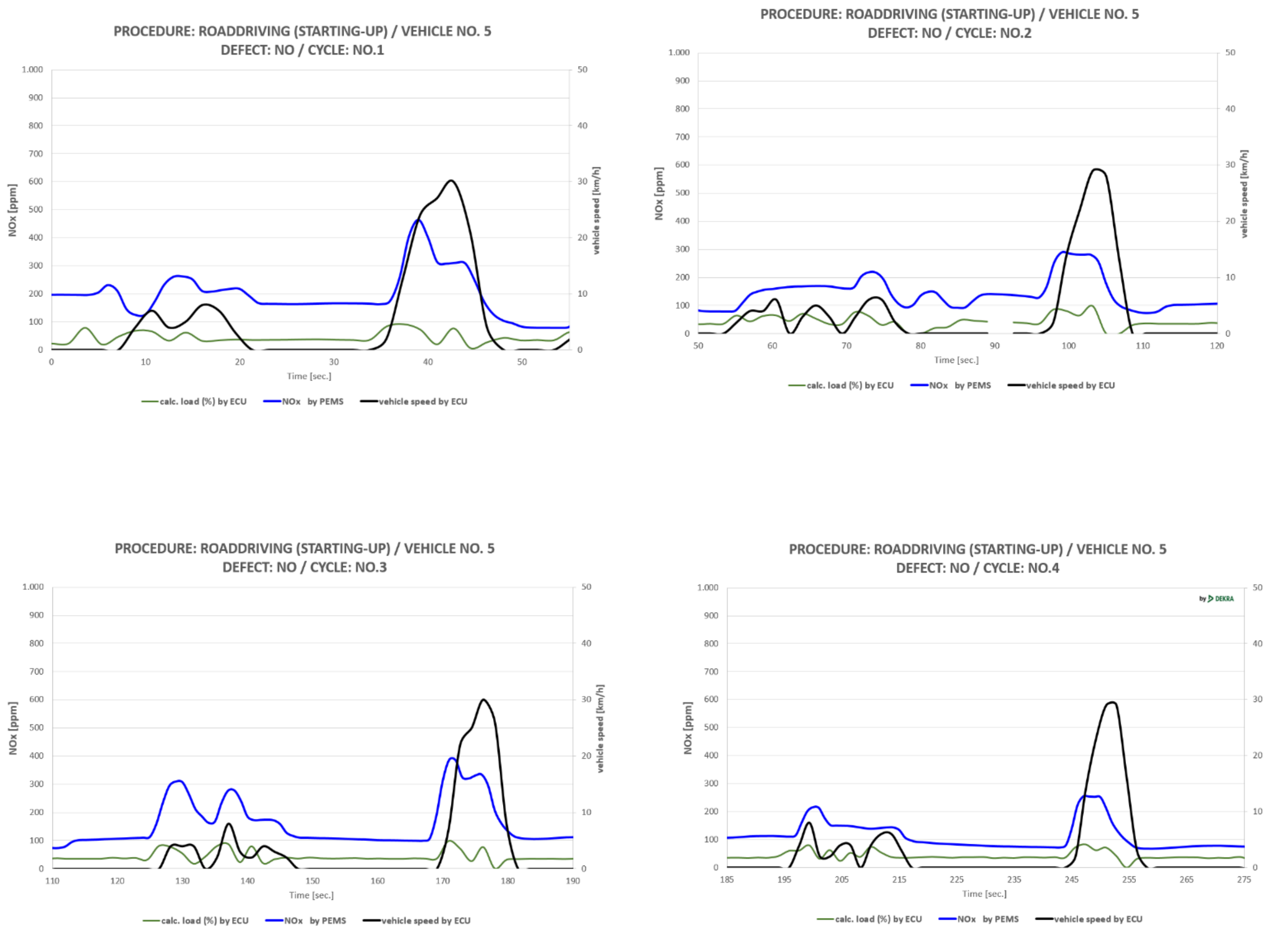


Figure 185: VEHICLE5 Short Test Drive, without defect

with defect

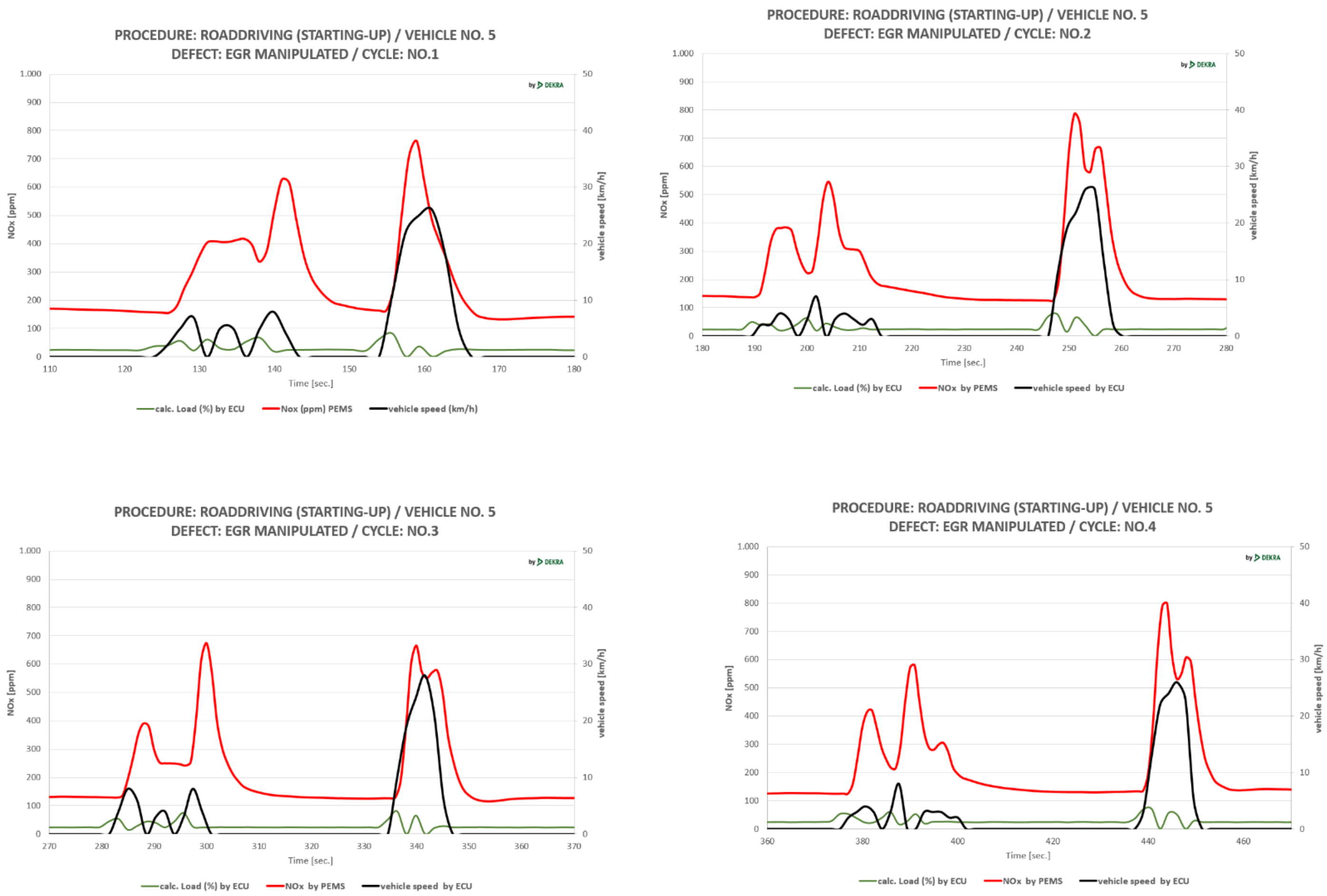


Figure 186: VEHICLE5 Short Test Drive, with defect

→ Level of NOx with defect is significant higher
As the installed failure is in this case (vehicle 5) minor (EGR, see chapter 4)

→ Also for very low vehicle speed (< 10 km/h) significant high NOx
This could be an alternative to a dyno-cycle

Summary of the Road - driving / start-up tests (vehicle 5):
(mean values of 4 cycles each (peaks))

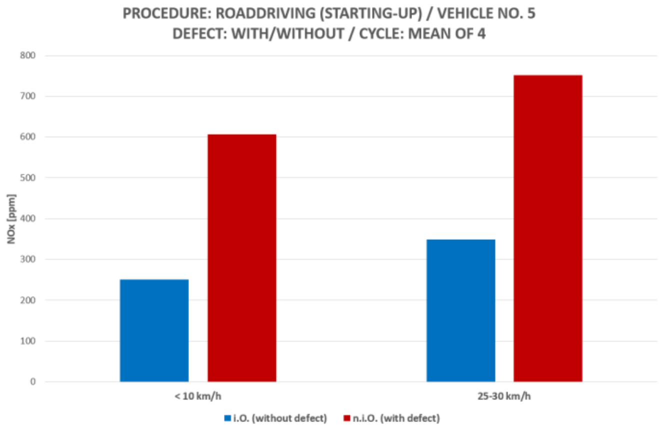


Figure 187: VEHICLE5 Short Test Drive, mean values

Ratio between vehicle i.o. and vehicle with defect:

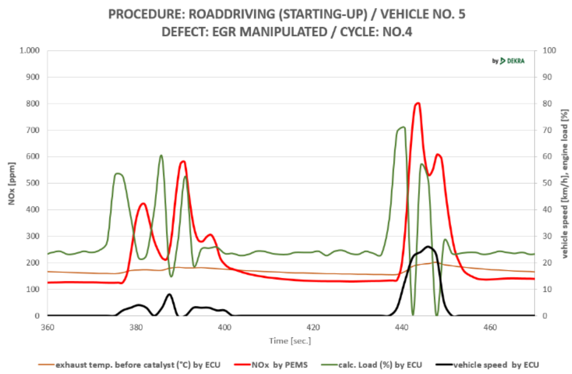
	25-30 km/h	< 10 km/h
Ratio n.i.o./i.o.	**2,2**	**2,4**

Table 59: VEHICLE5 Short Test Drive, ratio with and without defect

→ Also at low vehicle speed (start-up at < 10 km/h) it seems to be an alternative to an dyno - test
→ comparable conditions are necessary to described
→ more investigations are necessary

Further Investigations

Engine load



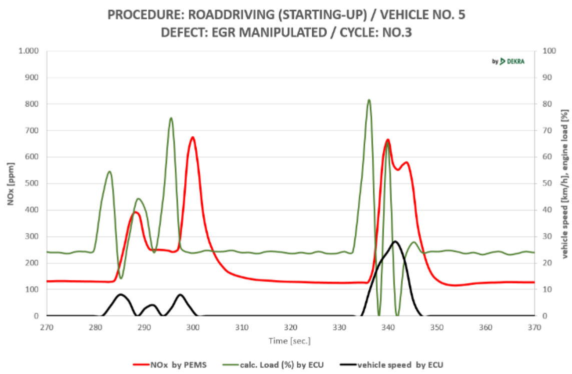


Figure 188: VEHICLE5 Short Test Drive, further investigations on engine load

→ Engine load is available by the ECU, but not within the standardized OBD
➔ using vehicle acceleration in combination with cal. Engine load and other conditions can be a definition for a high repeatability

Problems with the specific vehicle: None.

5.3.7.4. AVL Evaluation

Comparison: with/without defect

we measured

- original state ("without defect")
- EGR manipulated by removing the temperature sensor ("with defect", see No. 4)
  compared to the other vehicles this failure is very "small" because the leakage is small

without defect (original state) some examples of course

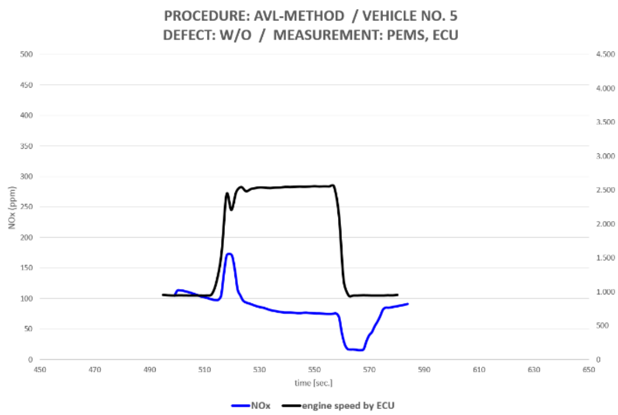
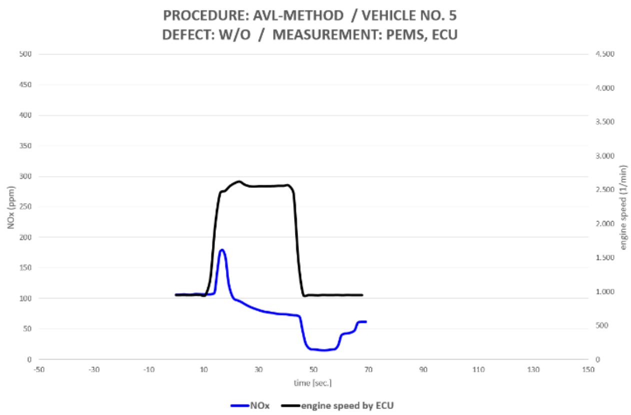
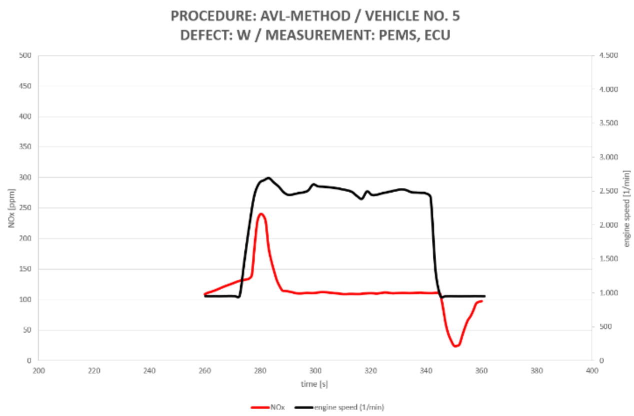


Figure 189: VEHICLE5 AVL cycle, without defect



with defect some examples of course



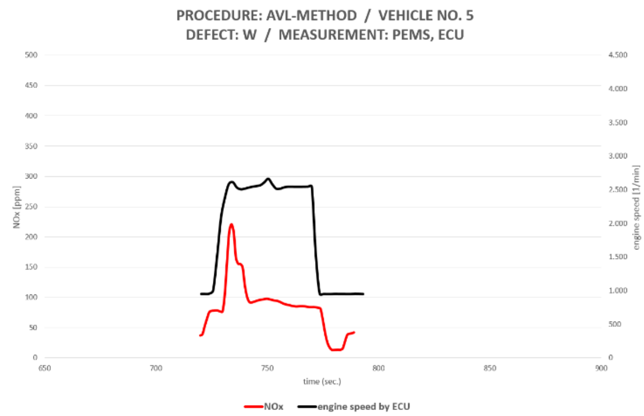


Figure 190: VEHICLE5 AVL cycle, with defect

without defect (original state) overview NOx peaks

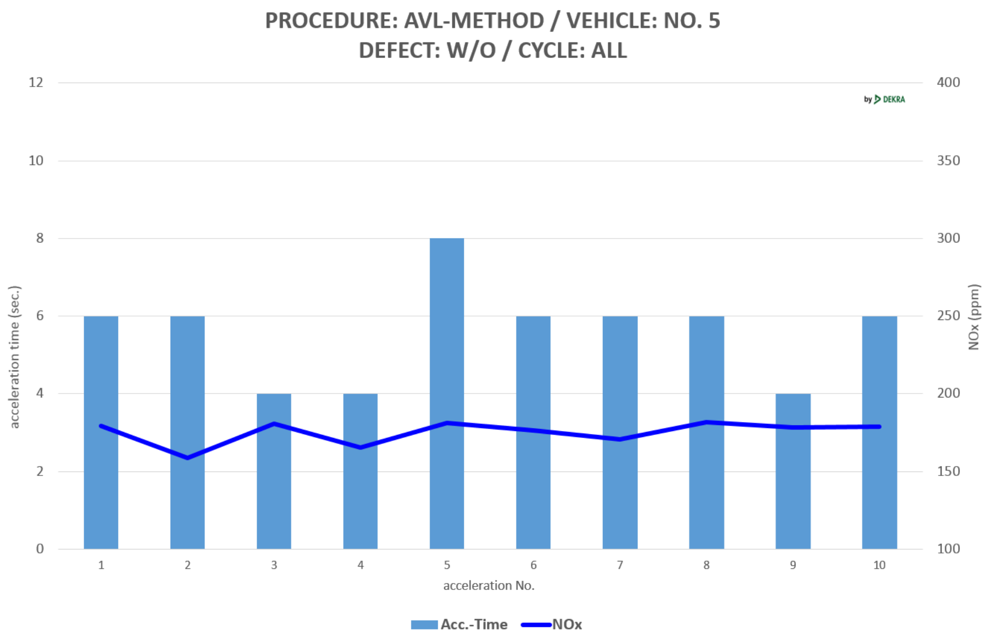


Figure 191: VEHICLE5 AVL cycle, without defect peak values

with defect overview NOx peaks

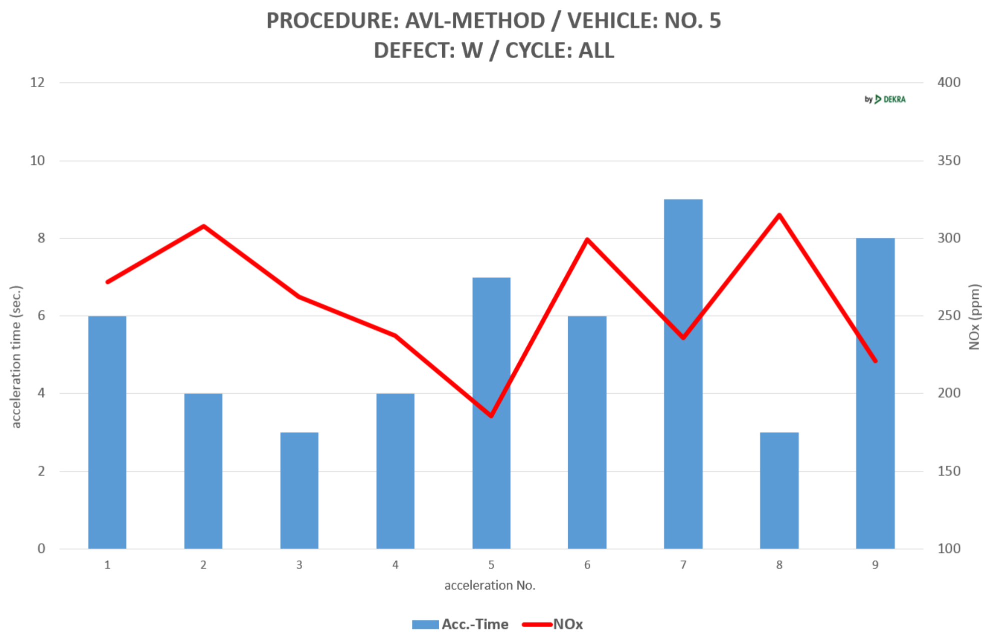


Figure 192: VEHICLE5 AVL cycle, with defect peak values

→ dependence acceleration time/NOx. Short acceleration time means high NOx peaks/long acceleration time means low NOx peaks
→ measurings without defect: variance of NOx is inside accuracy of measuring (PEMS)
→ higher values with defect

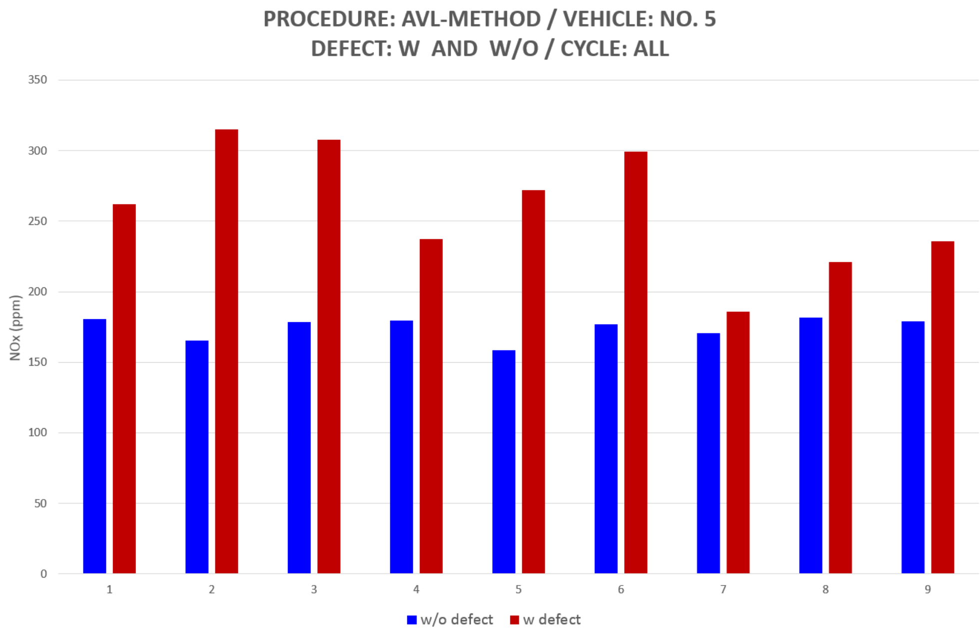


Figure 193: VEHICLE5 AVL cycle, comparison with and without defect

The diagram above is just to visualize the difference between "without" and "with" defect. The acceleration times was "accidentally" and are not comparable.

Ratios with/without defect:

Ratio n.i.o./i.o.	**1,5**

Table 60: VEHICLE5 AVL cycle, ratio with without defect

Further Investigations

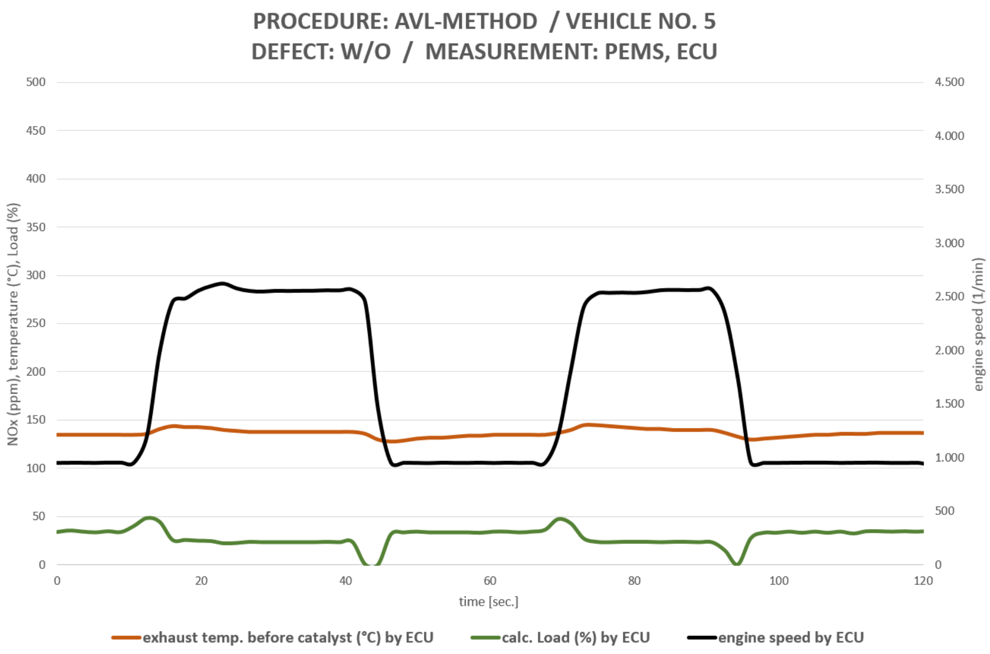


Figure 194: VEHICLE5 AVL cycle, further investigation

→ exhaust temperature is not very high at AVL-Method (< 200 °C) and engine load (by ECU) is not very high at AVL-Method (maximum 50%)

Problems with the specific vehicle:

No.
With stationary wheels, the engine is limited at 2.500 1/min (cut-off)

5.3.8. Reproduction of measurements ASM2050

Vehicle 1

Manufakturer: BMW; Type: X5; First registration: 12/2006

5 measurements:

Figure 195: VEHICLE1 ASM2050, reproduction of measurement (1)

Measurement cycles

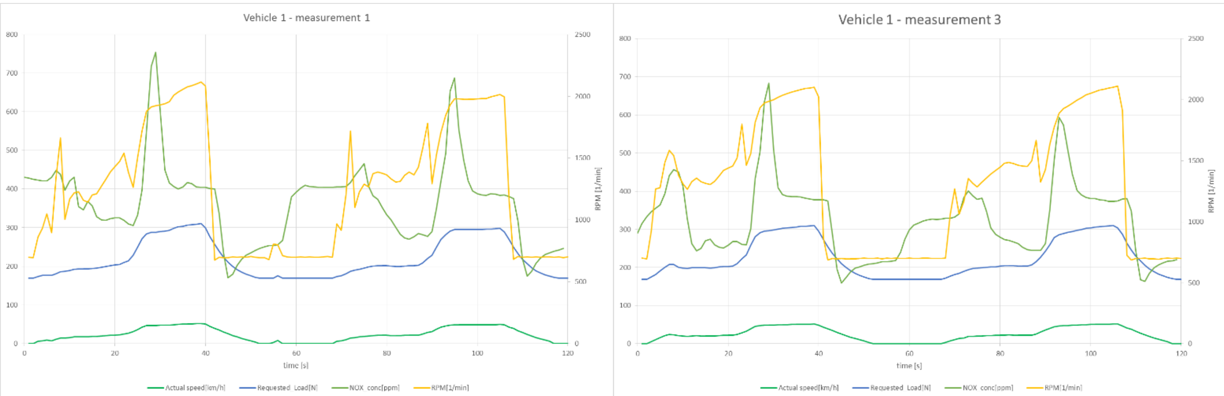


Figure 196: VEHICLE1 ASM2050, reproduction of measurement (2)

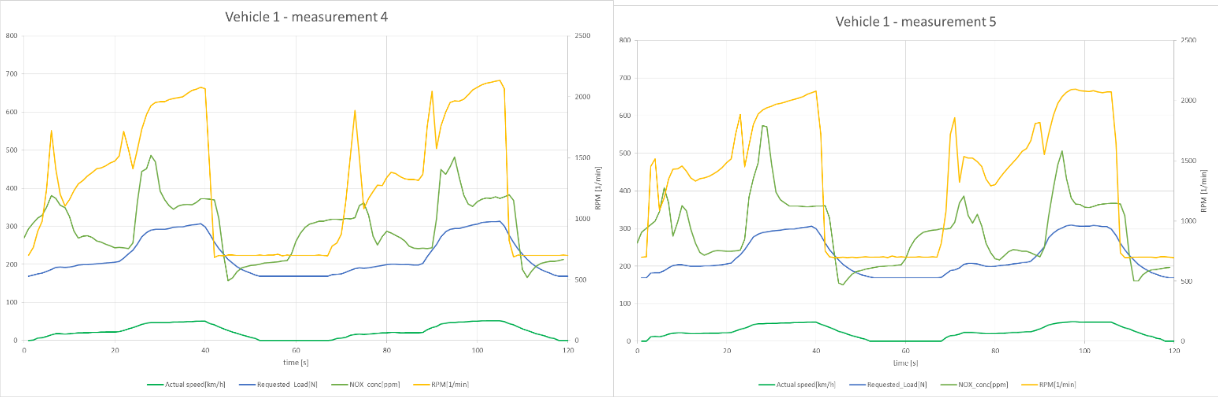


Figure 197: VEHICLE1 ASM2050, reproduction of measurement (3)

Vehicle 2
Manufakturer: VW; Type: Amarok

20 measurements:

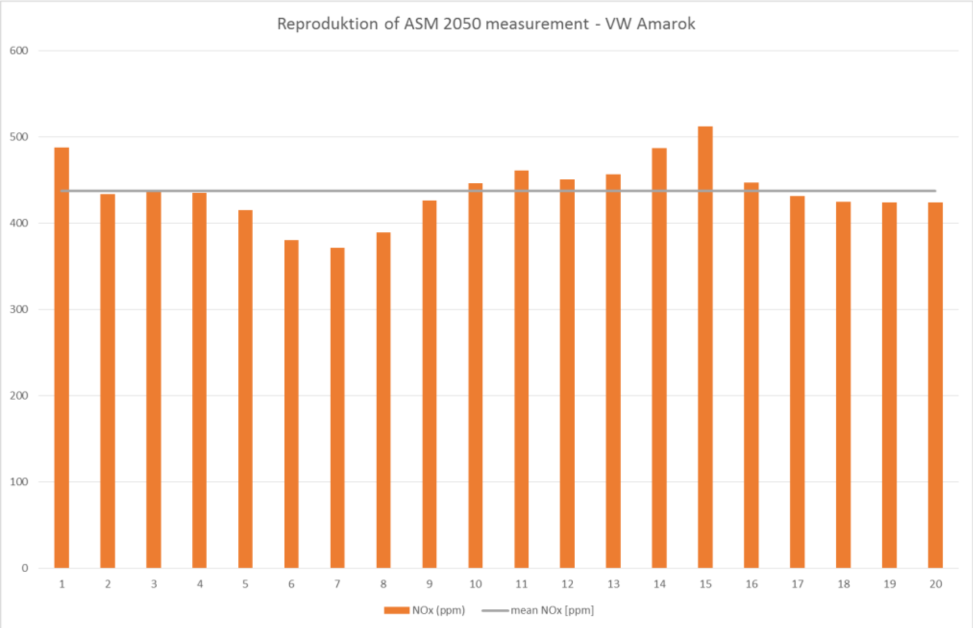


Figure 198: VEHICLE2 ASM2050, reproduction of measurement (1)

Measurement cycles

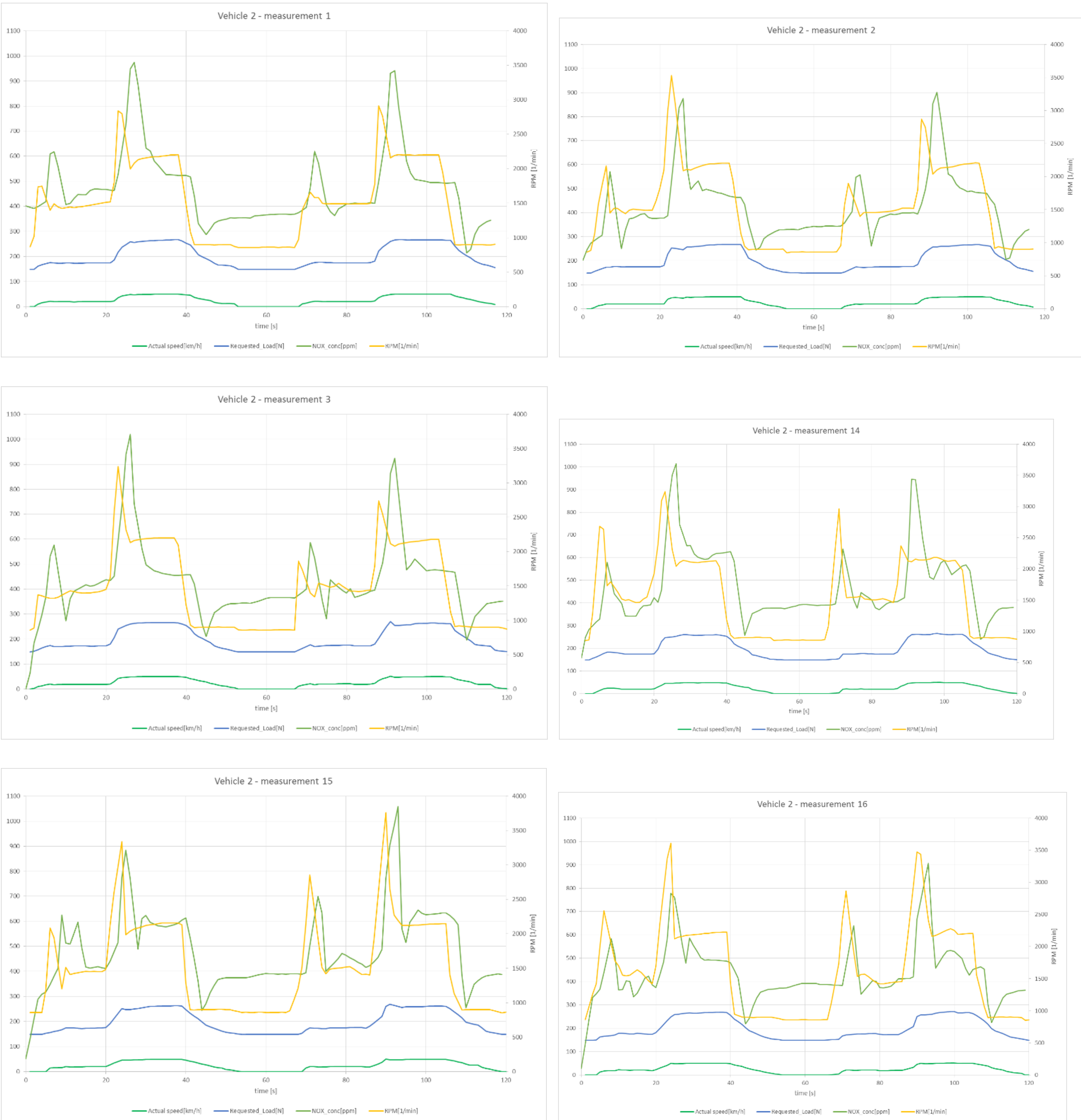


Figure 199: VEHICLE2 ASM2050, reproduction of measurement (2)

Vehicle 3

Manufakturer: VW; Type: Golf VI

15 measurements:

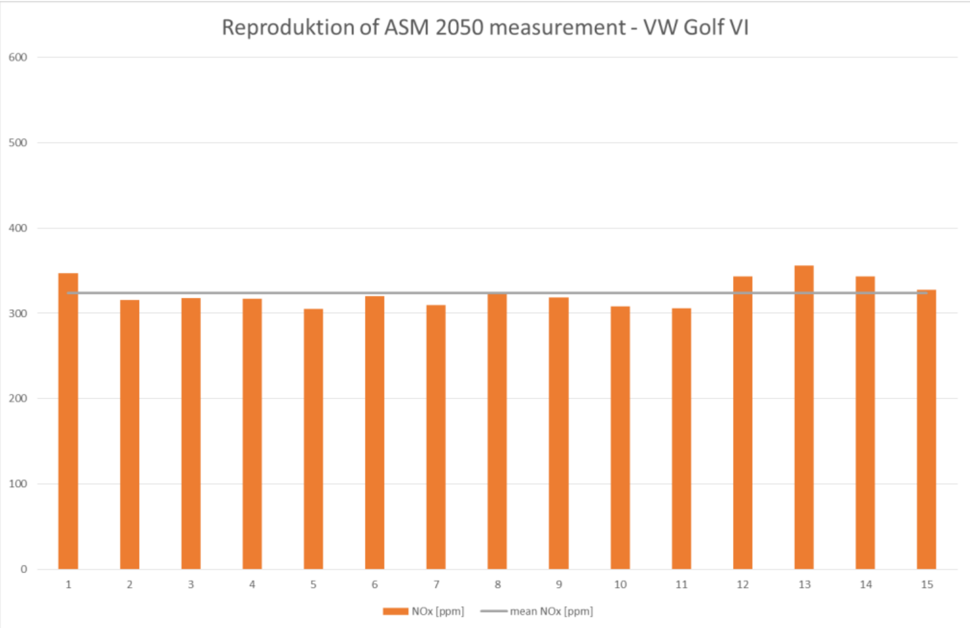


Figure 200: VEHICLE3 ASM2050, reproduction of measurement (1)

Measurement cycles

Figure 201: VEHICLE3 ASM2050, reproduction of measurement (2)

6. Field tests results

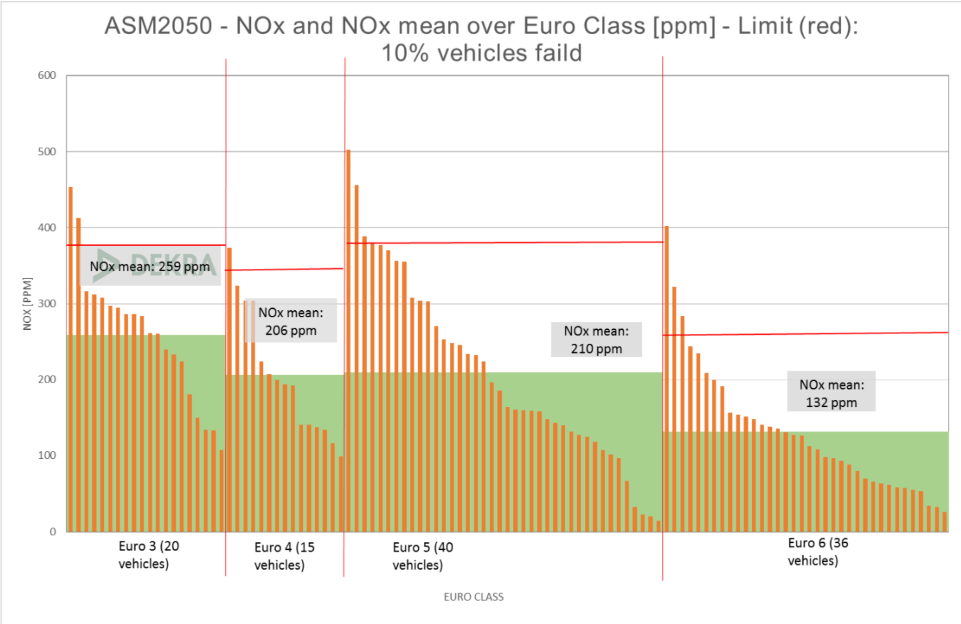
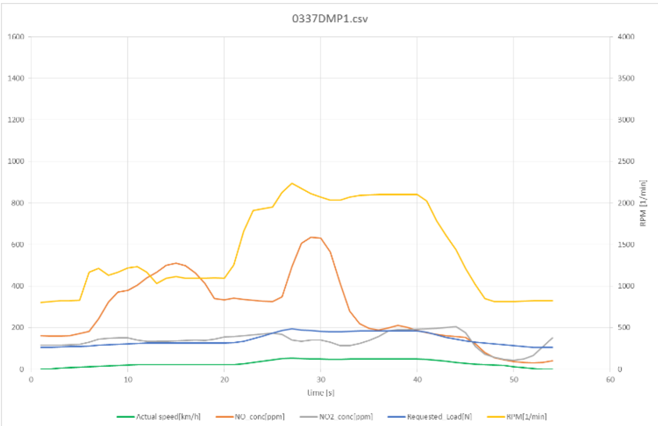
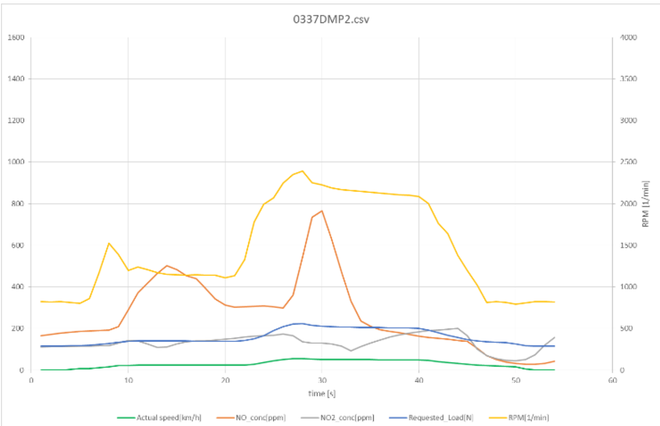
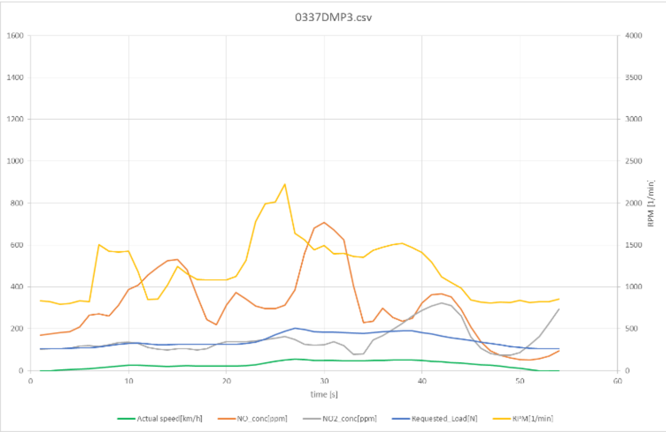


Figure 202: Field tests results NO_X and NO_X mean over Euro Class

Euro 3: The diagrams of the vehicle with the highest NOx value







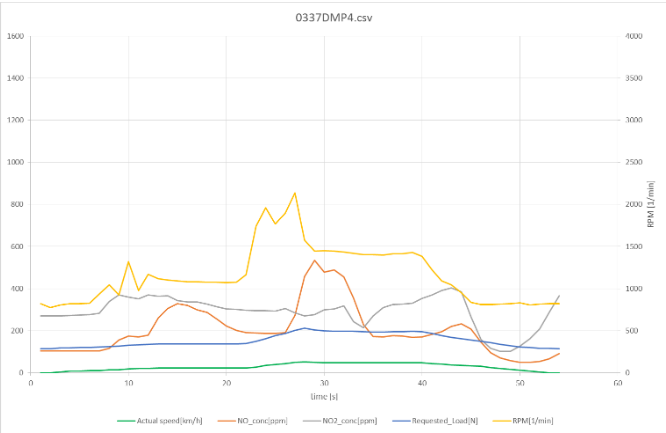


Figure 203: Field tests results, Euro 3: The diagrams of the vehicle with the highest NOx value

Euro 3: The diagrams of the vehicle with the lowest NOx value

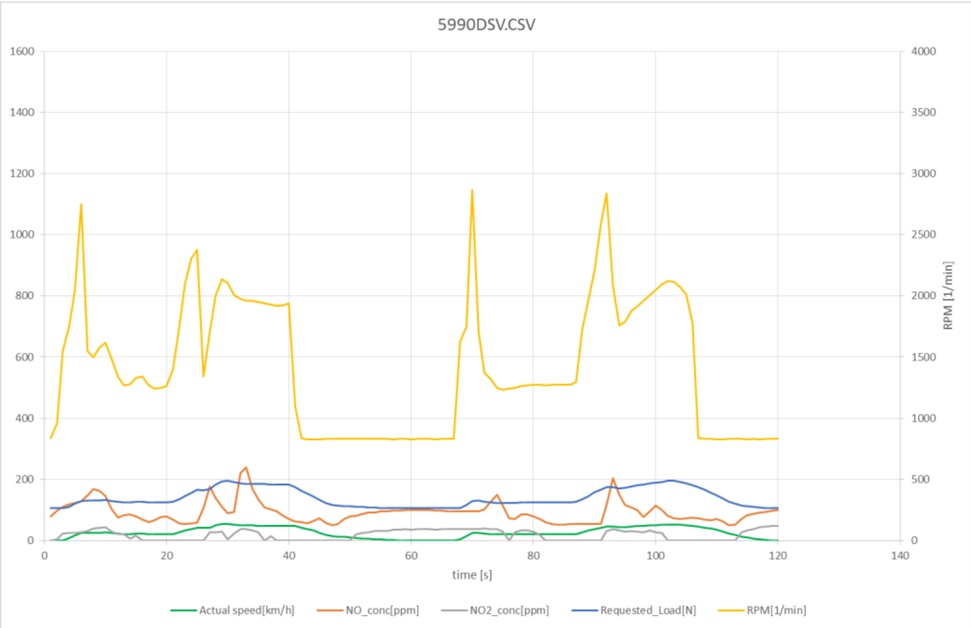


Figure 204: Field tests results, Euro 3: The diagrams of the vehicle with the lowest NOx value

Euro 4: The diagrams of the vehicle with the highest NOx value

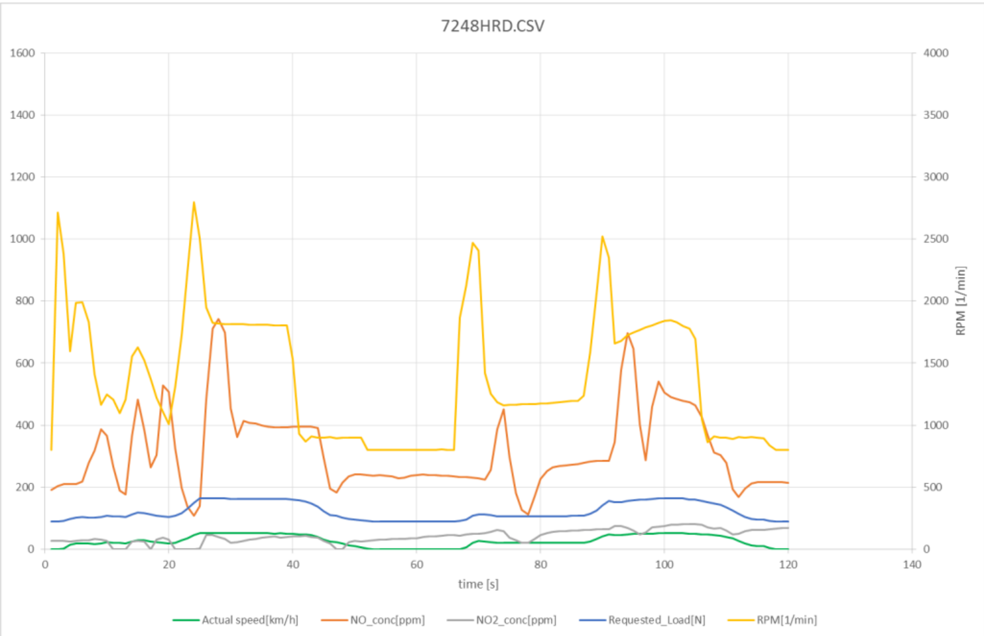
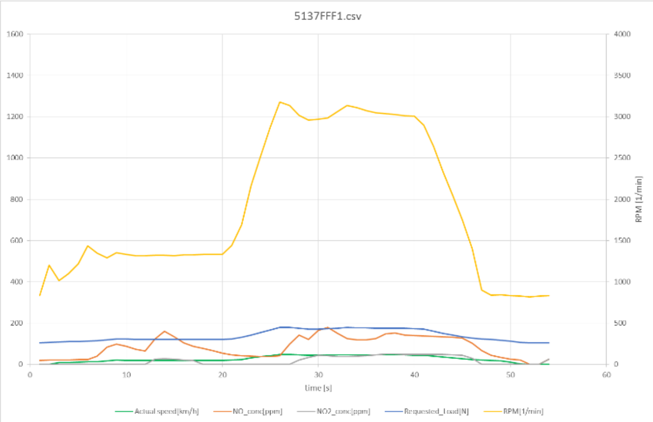


Figure 205: Field tests results, Euro 4: The diagrams of the vehicle with the highest NOx value

Euro 4: The diagrams of the vehicle with the lowest NOx value



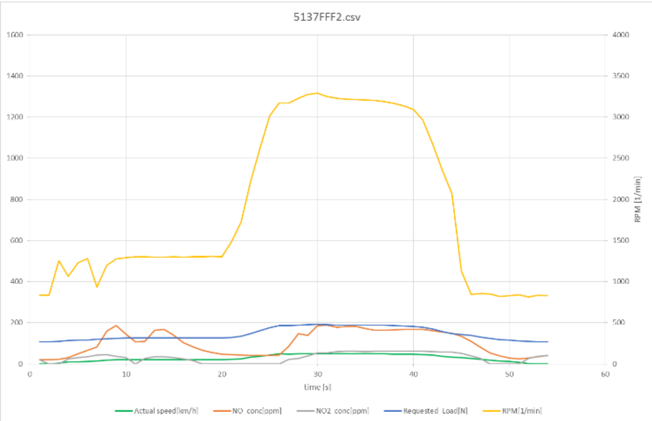


Figure 206: Field tests results, Euro 3: The diagrams of the vehicle with the lowest NOx value

Euro 5: The diagrams of the vehicle with the highest NOx value

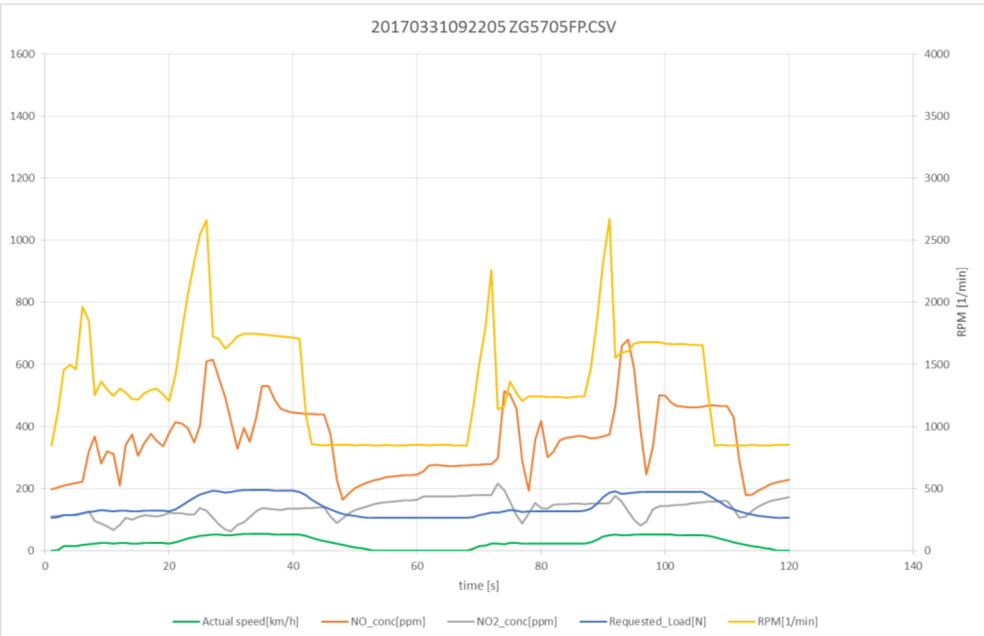


Figure 207: Field tests results, Euro 5: The diagrams of the vehicle with the highest NOx value

Euro 5: The diagrams of the vehicle with the lowest NOx value

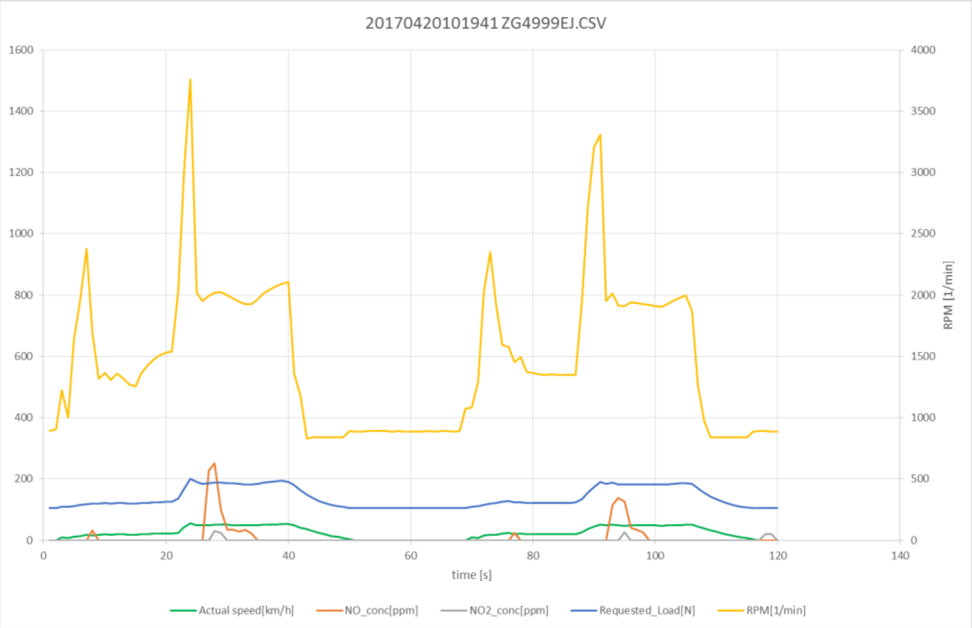


Figure 208: Field tests results, Euro 5: The diagrams of the vehicle with the lowest NOx value

Euro 6: The diagrams of the vehicle with the highest NOx value

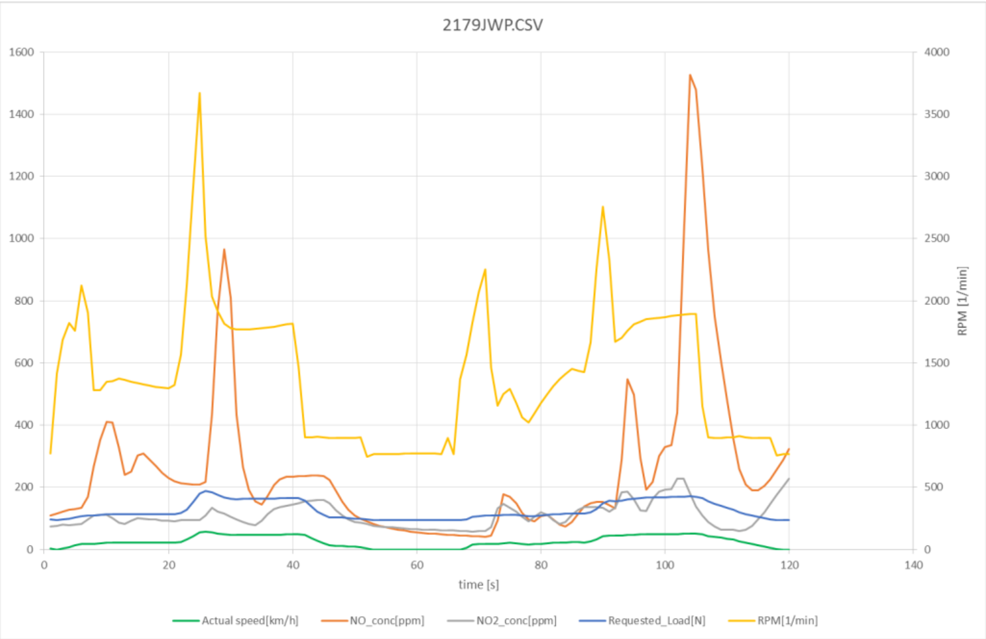


Figure 209: Field tests results, Euro 6: The diagrams of the vehicle with the highest NOx value

Euro 6: The diagrams of the vehicle with the lowest NOx value

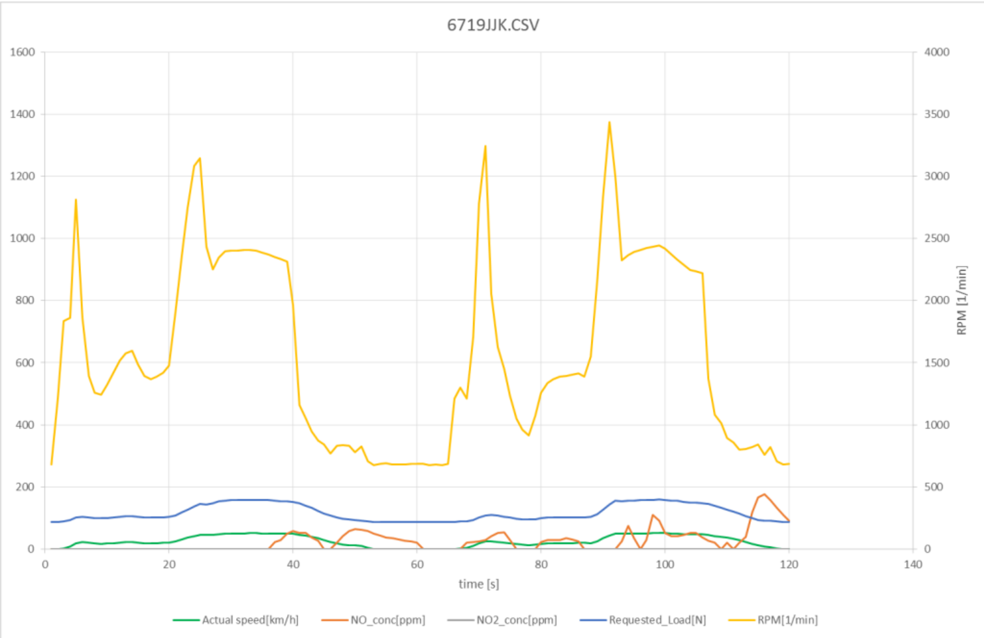


Figure 210: Field tests results, Euro 6: The diagrams of the vehicle with the lowest NOx value

Glossary of terms

The following table provides definitions for terms relevant to this document.

a	Acceleration in [m/s^2]
A	Frontal surface in [m^2]
ABS	Anti-lock braking system
ASM	Acceleration simulation mode
BAR	Oregon Bureau of Automotive Repair
BC	Black Carbon
CADC	Common Artemis driving Cycle
CARB	California Air Resources Board
CCFET	Capacitive-Coupled Field-Effect Transistor
CF	Conformity Factor
CO	Carbon monoxide
CO_2	Carbon dioxide
CUEDC	Composite Urban Emissions Drive Cycle
CVS	Constant volume sampling (system)
C_w	Drag coefficient
Cyl	Engine displacement in [cm^3]
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
DTC	Diagnostic trouble code
EF	Emission Factor
EGR	Exhaust gas recirculation
EOBD	European on-board diagnostics
EPA	Environmental Protection Agency
EU	European Union
Euro 1, 2, 3, …	Emission standards for passenger cars
Euro I, II, III …	Emission standards for large goods vehicles
FID	Flame ionization detector
FTIR	Fourier-transform Infra-red spectroscopy
FTP	(US) Federal Test Procedure
HC	Hydrocarbons
HDV	Heavy Duty Vehicle
HGV	Heavy Good Vehicles
I/M	Inspection and maintenance
ISO	International Organization for Standardization
k	Absorption coefficient
K	Kelvin, unit of measure for temperature
LDDV	Light-Duty Diesel Vehicles
LDV	Light Duty Vehicle

LLSP	Laser-Light-Scattering Photometry
LNT	Lean NO_x trap
m	Vehicle mass;
MAF	Mass Air Flow (sensor)
$\dot{m}_{air}$	Air Mass flow in [kg/h]
MIL	Malfunction indicator lamp
N	Revolutions per minute
NDIR	Non-dispersive infrared absorption spectroscopy
NDUV	Non-dispersive ultraviolet absorption spectroscopy
NEDC	New European Drive Cycle
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides ($NO + NO_2$)
O_2	Oxygen
O_3	Ozone
OBD	On-board diagnostics
OHMS	On-road Heavy-duty Emissions Measurement System
OIML	L'Organisation internationale de métrologie légale or The International Organization of Legal Metrology
PEMS	Portable Emission measurement system
PM	Particulate Matter
PN	Particulate Numbers
PTI	Periodic technical inspection
RC	Readiness code
RDE	Real Driving Emissions
rpm	Revolutions per minute
RSD	Remote Sensing Device
SAE	Society of Automotive Engineers
SCR	Selective catalytic reduction
THC	Total hydrocarbon emissions
US	United States
USEPA	United States Environmental Protection Agency
v	Vehicle speed expressed in [m/s]
VSP	Vehicle Specific Power
v_w	Wind velocity
WLTC	World-Harmonized Light-duty Vehicle Test Cycle
λ	Oxygen/Combustibles balance (Lambda)
ρ_{air}	Air density in [kg/m³]
$\rho_{remplissage}$	Engine filling ratio (Capelec)

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